NRL Memorandum Report 2249

A Study of the Feasibility of Using 35 GHz and/or 94 GHz as a Means of Improving Low Angle Tracking Capability

FRANK H. THOMPSON AND FRANK A. KITTREDGE

Search Radar Branch
Radar Division

May 1971

NAVAL RESEARCH LABORATORY
Washington, D.C.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)	2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Washington, D.C. 20390	UNCLASSIFIED
	2b. GROUP

3. REPORT TITLE

A STUDY OF THE FEASIBILITY OF USING 35 GHz AND/OR 94 GHz AS A MEANS OF IMPROVING LOW ANGLE TRACKING CAPABILITY

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

An interim report on a continuing problem.

5. AUTHOR(S) (First name, middle initial, last name)

Frank H. Thompson
Frank A. Kittredge

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
May 1971	42	10

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
NRL Problem R02-24	NRL Memorandum Report 2249
b. PROJECT NO. NAVAIRSYSCOM A5355352-652E-0F09905020	
c.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

10. DISTRIBUTION STATEMENT

Approved for public release; distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Air Systems Command Washington, D.C. 20360

13. ABSTRACT

Millimeter-wave radar systems ~~have been~~ analyzed to determine their low-angle tracking capability. The narrow beamwidths that can be obtained at these frequencies with antennas of reasonable size permit a target to be resolved in angle from its image. Because of the severe effects of tropospheric attenuation, the study ~~has been~~ limited to two frequency bands, 35 and 94 GHz, which lie near the principal minima of the attenuation curve. Theoretical expressions for radar tracking accuracy, together with existing attenuation data, have been used to compare the performance of realizable 35-GHz (K_a-band) and 94-GHz (W-band) radars with that of an existing 5280-MHz (C-band) radar. An antenna diameter of 12 feet was assumed for all three systems.

It is found that the tracking range of the millimeter-wave radars is limited severely by atmospheric effects and by state-of-the-art transmitters and receivers. But there is a significant increase, as compared with the C-band radar, in the extent of the low angle region within which precision (0.1 mil) tracking can be realized. For example, the K_a-band radar at a height of 50 feet can maintain a precision track on a 0.018 square meter target at a 500 feet elevation to a range of 10,000 yards and the W-band radar to 22,000 yards (in clear weather), as compared with 3000 yards for the C-band radar. The C-band radar has no precision tracking capability against a target at a 100 foot elevation, but the K_a-band and W-band systems have a useful range to 2000 and 5400 yards respectively.

(Abstract Continued)

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6801

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Low-angle Tracking						
Multipath Error						
Millimeter-wave Tracking Radar						

In the absence of adequate eperimental data, no attempt has been made to include the effects of tropospheric refraction and ducting. These effects may be severe in certain circumstances. Nevertheless, the use of millimeter waves appears to offer a significant improvement in precision radar tracking at low elevation angles.

CONTENTS

ABSTRACT

Millimeter-wave radar systems have been analyzed to determine their low-angle tracking capability. The narrow beamwidths that can be obtained at these frequencies with antennas of reasonable size permit a target to be resolved in angle from its image. Because of the severe effects of tropospheric attenuation, the study has been limited to two frequency bands, 35 and 94 GHz, which lie near the principal minima of the attenuation curve. Theoretical expressions for radar tracking accuracy, together with existing attenuation data, have been used to compare the performance of realizable 35-GHz (K_a-band) and 94-GHz (W-band) radars with that of an existing 5280-MHz (C-band) radar. An antenna diameter of 12 feet was assumed for all three systems.

It is found that the tracking range of the millimeter-wave radars is limited severely by atmospheric effects and by state-of-the-art transmitters and receivers. But there is a significant increase, as compared with the C-band radar, in the extent of the low angle region within which precision (0.1 mil) tracking can be realized. For example, the K_a-band radar at a height of 50 feet can maintain a precision track on a 0.018 square meter target at a 500 foot elevation to a range of 10,000 yards and the W-band radar to 22,000 yards (in clear weather), as compared with 3000 yards for the C-band radar. The C-band radar has no precision tracking capability against a target at a 100 foot elevation, but the K_a-band and W-band systems have a useful range to 2000 and 5400 yards respectively.

In the absence of adequate experimental data, no attempt has been made to include the effects of tropospheric refraction and ducting. These effects may be severe in certain circumstances. Nevertheless, the use of millimeter waves appears to offer a significant improvement in precision radar tracking at low elevation angles.

PROBLEM STATUS

This is an interim report; work continues on other phases of the problem.

AUTHORIZATION

NRL Problem 53R02-24
NAVAIRSYSCOM A5355352-652E-0F09905020

A STUDY OF THE FEASIBILITY OF USING 35 GHz AND/OR 94 GHz
AS A MEANS OF IMPROVING LOW ANGLE TRACKING CAPABILITY

INTRODUCTION

The Pacific Missile Range requires high precision radar tracking of airborne targets, including those at low elevation. Specific requirements for real time accuracy are ± 10' in three dimensions (1). However, at low angles the multipath problem arising from the reflection of echo energy from the ocean surface causes elevation-angle tracking errors exceeding the required tracking precision. The magnitude of the error is a function of the intensity of the reflected energy received in the monopulse difference-signal channel. This intensity is directly related to the shape of the difference-signal pattern. The basic precision tracking radar used at the Pacific Missile Range is the C-band AN/FPS-16 monopulse tracking radar with a 12-foot antenna. The difference-signal pattern of this antenna is sufficiently broad, including significant sidelobes, to cause excessive multipath tracking errors in the elevation angle region below 5 degrees. Since the multipath phenomenon is directly related to antenna pattern width, the unusable low angle region could be reduced, for a given antenna size, by increasing the radar frequency.

The objective of this report is to present an analysis of the use of an auxiliary millimeter-wave radar to supplement the tracking capability of the AN/FPS-16 at the lower elevation angles. This is a preliminary analysis based on data and theoretical relationships available in the literature, and will be followed by measurements with a 35-GHz tracking system at the NRL Chesapeake Bay Division. The assumptions in the analysis are that the C-band portion of the radar is the primary tracking system, and that an additional monopulse feed is added, providing a dual-frequency capability.

A new reflector of closer tolerances is required, but the 12-foot diameter is retained in this analysis to allow the same servo performance to be realized with the existing pedestal and servo system.

Well documented performance (2) of the AN/FPS-16 (XN-1) radar is used as a basis for C-band performance. Only 35-GHz (K_a-band) and

94-GHz (W-band) frequencies have been considered, in view of the excessive atmospheric attenuation in the remainder of the millimeter-wave range. The purpose of the study has been to determine the angle and height error in the low angle region at each of these frequencies, taking into account multipath error and all other major sources of error predictable from information available in the literature. Little is known of millimeter-wave refractive effects in the lower atmosphere on over-water paths. An experimental program is needed to determine the magnitude of the elevation-angle errors attributable to these effects.

DESCRIPTION OF SYSTEMS

A comparative study was made of the tracking accuracy of a C-band (5280-MHz) system, a K_a-band (35-GHz) system and a W-band (94-GHz) system at low angles over the sea. The parameters of the three vertically polarized radars were taken to be identical with the exception of the transmitter frequency and power, the antenna gain, and the system losses. The parameters of each system are listed in Table 1. The C-band parameters are those of an existing AN/FPS-16 radar, while those given for K_a and W-band are approximately state-of-the-art.

PERFORMANCE OF THE AN/FPS-16 (XN-1)

The performance of the AN/FPS-16 (XN-1) radar was determined by an extensive series of tests conducted in 1956 by the Radio Corporation of America under supervision of the Naval Research Laboratory (2). An important phase of these tests was devoted to tracking 6-inch aluminum spheres that were carried aloft inside free balloons. After release, the spheres were acquired and tracked by the radar, and a series of film bursts was made with a boresight camera. During these tests the balloons rose to a height of approximately 50,000 feet and drifted less than 30 miles from the radar site, maintaining a sufficient elevation angle to exclude multipath effects. Range and angle-tracking errors were measured to verify theoretical error predictions.

Figure 1, which has been reproduced from the RCA report (2, Fig. 4-21), is typical of the data obtained from the sphere-tracking tests. Elevation

Table 1

System Configurations Upon Which Calculations Were Based

Parameter	C-Band AN/FPS-16 (XN-1)	K_a-Band	W-Band
Frequency, GHz	5.28	35	94
Peak Power, kW	1000	100	4
Pulse Width, μsec	0.25	0.25	0.25
PRF, pulses per second	1280	1280	1280
Antenna Diameter, feet	12	12	12
Antenna Gain, dB	44.5	61.0	69.5
Antenna Beamwidth, degrees	1.10	0.166	0.062
Polarization	Vertical	Vertical	Vertical
Receiver Noise Figure, dB	11	11	11
Receiver Bandwidth, MHz	8	6	[illegible]
Servo Bandwidth, Hz	0.5	0.5	0.5
System Losses, dB (T&R)	2.0	4.0	9.0
One-way Atmospheric Attn, dB/km			
In fair weather	0.008	0.15	0.69
In 4 mm/hr Rain	0.016	0.62	1.90

angle noise is plotted as a function of target range on a log-log scale, along with three straight lines representing the theoretical contributions of linear target error, tropospheric propagation error and thermal noise error. Many other sources of error were considered and found to be negligible.

Glint Errors

The linear target error, glint, is taken to be 3 inches, independent of range. Its contribution to the angle noise, in milliradians,

$$\sigma_G = \frac{1}{12} \quad \frac{1}{R} \quad \text{mils} \tag{1}$$

where R is the range in thousands of yards. The slope of the linear error curve is -1.

Tropospheric Propagation Error

The tropospheric propagation error due to inhomogeneities in the atmosphere is calculated from the expression

$$\sigma_p = 2 \times 10^{-3} \sqrt{\overline{\Delta N^2}} \quad \sqrt{L/L_o} \qquad \text{mils} \tag{2}$$

where

$\sqrt{\overline{\Delta N^2}}$ is the RMS variation of the refractivity (in N units) over an average "blob", abbreviated in Fig. 1 as ΔN

L is the path length through the disturbed medium, taken to be the slant range of the target in feet

L_o is the average blob length in feet.

In the particular test shown in Fig. 1, ΔN was taken to be 0.5 and L_o to be 50 feet. The slope of the propagation-error curve is $+\frac{1}{2}$.

Receiver Thermal Noise Error

The contribution of receiver thermal noise to angle tracking error is (3, p. 283)

$$\sigma_t = \frac{\theta_e}{k_m\sqrt{B\tau}\,(S/N)\,(f_r/\beta_n)} \qquad \text{mils} \tag{3}$$

where

θ_e is the elevation beamwidth in milliradians

k_m is the error slope factor = 1.57

B is the IF bandwidth

τ is the pulse length

S/N is the signal to noise ratio

f_r is the pulse repetition frequency

β_n is the servo bandwidth.

The formula is valid when the signal to noise ratio is greater than 4. In Fig. 1 the servo bandwidth is taken to be 0.5 Hz. The slope of the rms thermal-noise error curve is + 2, since the signal to noise power ratio varies inversely as the fourth power of the range.

Multipath Error

Barton (4, p. 5-41) has calculated the elvation-angle multipath error of the AN/FPS-16 (XN-2) radar, when tracking at low angles over land or sea, using the equation

$$\sigma_M = \frac{\theta_e \rho}{\sqrt{8 A_s}} \quad \text{mils} \qquad (4)$$

where

ρ is the reflection coefficient of the surface

A_s is the ratio of the gain at the peak of the monopulse sum pattern to the gain of the difference pattern in the direction of the reflected ray.

The results are shown in Fig. 2, which has been reproduced from Fig. 5-14 of Reference 4. Curves are shown for perfectly reflecting earth, for land having a reflection coefficient of 0.3, and for sea water, whose reflection coefficient is a function of grazing angle. The vertical beamwidth of the antenna is 1.2 degrees, and the multipath error is moderate down to

2.0 degrees, or just less than 2 beamwidths. Below this angle, the error rises rapidly. Because the errors are large and somewhat uncertain at the lowest angles, the error curves shown in the remainder of this report have been cut off at an elevation-angle/vertical-beamwidth ratio of 0.25.

CALCULATED ANGLE ERRORS OF THE K_a AND W-BAND RADARS

The four components of elevation-angle tracking error of the C-band AN/FPS-16 radar, described in the preceding paragraphs, were extrapolated to the K_a and W-band systems by making the necessary corrections for atmospheric attenuation, signal-to-noise ratio, and antenna beamwidth. These corrections are discussed separately in the following paragraphs.

Glint (Target Angle Scintillation Error)

The target error, σ_G is the same for all three radars.

Tropospheric Propagation Error

The propagation error, σ_p, is also independent of the radar system. However, values of the RMS variation of refractivity and average blob length were selected which are typical (3, p. 489) of an over-water path: $\Delta N = 1$ and $L_o = 400$ feet.

Thermal Noise Error

Equation (3) for the angle error due to receiver thermal noise requires correction (3, p. 284) if it is to be used at values of the signal-to-noise ratio less than 4. The servo system bandwidth, β_s, tends to be reduced from its large-signal value, β_n, in accordance with the relation

$$\beta_s = \beta_n/C_a \qquad (5)$$

where C_a is the detector loss factor and is equal to

$$(S + N)/S \text{ or } 1 + \frac{1}{S/N}$$

The detector loss factor increases with decreasing signal-to-noise ratio, and the effective servo bandwidth decreases. In practice, this is unacceptable; the bandwidth must be maintained reasonably constant to preserve tracking performance. If, then, β_s is independent of signal-to-noise ratio, the large-signal bandwidth, β_n, varies as

$$\beta_n = C_a \beta_s \tag{6}$$

Substitution of equation (6) into equation (3) yields an expression for thermal-noise error that is valid at all values of signal-to-noise ratio:

$$\sigma_t = \frac{\theta_e}{k_m \sqrt{B\tau\ (S/C_a N)(f_r/\beta_s)}} \tag{7}$$

Elevation-Angle Multipath Error

Most calculations of the low-angle multipath geometry use the convenient simplifying assumption that the target elevation angle, with respect to the radar, is equal to the depression angle of the image or reflected signal. However, for very low altitude targets where the radar height above the reflecting surface is a significant portion of the target altitude it is necessary to calculate the elevation angle and image angle separately. Therefore, the elevation and incident angles, Fig. 3, were calculated using the equations:

$$\theta_e = \frac{h_t - h_r}{3R} \text{ mils} \tag{8}$$

$$\theta_i = \frac{h_r + h_t}{3R} \text{ mils} \tag{9}$$

where the heights h are in feet and R is in thousands of yards. These curves were subsequently related to the reference curve ($\rho = 1$) of Fig. 2 with the equation

$$E_T = \frac{1}{2}(\theta_e + \theta_i) \tag{10}$$

because Fig. 2 used the reflection angle equals twice the elevation angle criterion.

ATMOSPHERIC ATTENUATION

Hoffman, Wintraub and Garber report (5, abstract) that the attenuation at W-band is 0.69 dB/km on a fair day in California, when the temperature is 20° C and the absolute humidity is 12.5 g/m^3. Further, the attenuation increases to 1.9° dB/km in 4 mm/hr rain. These values have been adopted in the present study as representative of the attenuation to be expected at W-band on the Pacific Missile Range.

No experimental values of attenuation at K_a-band were immediately available. Therefore, the W-band values were extrapolated to this frequency by use of the theoretical curves of LeFande (6). In his Fig. 3, LeFande shows the oxygen and water vapor attenuation at 15°C and 7.5 g/m^3 absolute humidity to be 0.11 dB/km at K_a-band and 0.49 dB/km at W-band. If these values are multiplied by the factor 0.69/0.49 to obtain agreement with the W-band attenuation measured by Hoffman et al. at a higher temperature and humidity, the fair-weather attenuation at K_a-band is found to be 0.15 dB/km.

To extrapolate the attenuation due to rainfall at 4 mm/hr, values were read from LeFande's Figure 12 and found to be 2.57 dB/km at 94 GHz and 1.00 dB/km at 35 GHz. The ratio, 0.389, was then applied to the measured value, 1.90 - 0.69 = 1.21 dB/km, to obtain the extrapolated value, 0.47 dB/km. Thus the K_a-band attenuation in 4 mm/hr rain was estimated at 0.47 + 0.15 = 0.62 dB/km.

The values of attenuation at C-band were taken from Reference (4, p. 5-7).

CALCULATIONS

A time sharing computer was used to calculate the RMS sum (σ_T) in mils of the elevation-angle errors due to glint (σ_G), thermal noise (σ_t), random propagation (σ_p) and multipath (σ_M) over a smooth sea, using flat-earth geometry. The calculations were made as a function of target height, slant range, weather (clear or 4 MM/hr. rain), sea reflection coefficient and target cross section. The elevation-angle

error was then converted to height error (σ_n) using the formula

$$\sigma_n = 3R\sigma_T \text{ feet.} \tag{11}$$

A least squares curve fitting computer routine was used to program the calculated sea reflection-coefficient curves of Ohman (7).

The computer was constrained not to print out errors under any of the following conditions:

1. The signal-to-noise ratio was less than -20 dB
2. The elvation-angle of the target was less than one quarter of a vertical beamwidth (8, p. 147)
3. The target was beyond the radar horizon
4. The elevation-angle error of the target was greater than 1 mil

DISCUSSION

Precision tracking accuracy of 0.1 mil may be realized with field instrumentation radars (9, p. 185). However, the real-time data accuracy of ± 10 feet (3.3 feet RMSO required by the Pacific Missile Range) was used as the criterion for vertical tracking accuracy evaluation. Figures 4, 5, 6, 7, and 8 show the individual and total system elevation errors in mils, RMS, versus slant range in thousands of yards. The curves represent C, K_a, and W-band radar systems, at a 50-foot height, tracking a 0.018-square meter target over smooth water at an altitude of 100 feet in clear and rainy (4 mm/hr) weather. These figures were chosen to show the particular effects that limit tracking accuracy. The horizontal line marked "tracking limit" represents an elevation-angle error of one-sixth beamwidth. This is Barton's criterion for probable loss of track (8, p. 215) without additional data processing.

The curves in Fig. 9 thrugh 24 show the slant ranges attainable for the specified height error. These curves also show the possible gains in low altitude tracking with millimeter wave systems.

A further study of Fig. 4 through 8 revealed the predominant component error responsible for the height error at the particular slant ranges. Multipath error dominates all three systems when they are tracking a target with a 100 foot altitude. Multipath error also dominates the C-band system and the K_a-band system when they are tracking a target with a 500 foot altitude. However, multipath error becomes insignificant for the W-band system tracking a target with a 500 foot altitude and propagation losses become the predominant component error.

Multipath is the main contributor to the 3.3 foot RMS height error of the C-band system. The slant ranges to a target at an altitude of 100 feet and 500 feet are 2000 yards and 5400 yards. Changing the target area from 0.018-square meter to 1.0-square meter (17.44 dB) or introducing a 4 MM/hr rainfall has no noticeable effect.

An examination of the height error curves for the K_a-band system shows an increase in slant range for the conditions named above. The slant ranges were increased to 4000 yards and 10,500 yards for target altitudes of 100 feet and 500 feet. Again, changing the target area or introducing rainfall has no noticeable effect on the major component error contributed by multipath.

A further increase in the slant range associated with a 3.3 feet RMS height error and a transition from multipath to propagation loss domination is indicated by the W-band system height error curves. For example, the slant range of 6200 yards for a target at 100 feet is not affected by changing the target area or introducing rainfall. But the target at 500 feet is affected by a change in the target area and rainfall. Changing the target size from 0.018-square meter to 1.0-square meter increases the slant range from 18,600 yards and 21,100 yards. A 4 mm/hr rainfall decreases the slant ranges to 11,100 yards and 14,300 yards. The slant ranges associated with a height error of 3.3 feet RMS are summarized in Table 2.

Table 2

Maximum Range versus 3.3 ft. RMS Height Error
T = Typical, R = Rain

Frequency Band	Target Height, h_t Ft.	Target Cross Section, σ M^2	Weather	Range K Yds.
C	100	0.018 or 1	T or R	2.0
C	500	0.018 or 1	T or R	5.4
K_a	100	0.018 or 1	T or R	3.9
K_a	500	0.018 or 1	T or R	10.5
W	100	0.018 or 1	T or R	6.2
W	500	0.018	T	18.6
W	500	0.018	R	11.1
W	500	1	T	21.1
W	500	1	R	14.3

CONCLUSIONS

Raising the radiated frequency of a tracking system from C-band to K_a-band or W-band improves the low angle tracking capability. This is a direct result of being able to track to smaller elevation-angles before the onset of errors caused by multipath propagation. Also, the thermal noise error is proportional to antenna beamwidth. However, as the frequency is raised, atmospheric propagation losses become much more severe, particularly at W-band, with the result that tracking accuracies are not as good as would be expected on a strictly geometric basis. This limits the performance at long range, but at shorter ranges millimeter-wave radar offers a very considerable improvement in tracking accuracy.

A target 100 feet above a sea surface is very difficult to track accurately in elevation from an antenna height of 50 feet (10, page 25). In fact, the C-band system is limited to a slant range of 2000 yards for a height error of 3.3 feet RMS and never attains the precision tracking error of 0.1 mil RMS. The K_a-band and the W-band systems have a tracking capability of 3900 yards and 6200 yards for a height error of 3.3 feet RMS. Moreover, the precision tracking error of 0.1 mil RMS is valid for slant ranges of 2000 yards and 5400 yards.

Decreasing the antenna beamwidth by increasing the transmitted frequency can improve low-angle tracking capability. An examination of the curves shown in Figs. 4 through 10 indicates a predominate multipath elevation angle component error. A closer examination shows this error is reduced when the transmitted frequency is increased. In short, the multipath elevation-angle component error may be reduced to an insignificant amount by increasing the transmitted frequency. However, the increase in frequency is accompanied by a large increase in propagation losses. Figure 8 shows that the predominant elevation-angle error for a W-band system tracking a target with a 500 foot elevation is due to propagation losses.

REFERENCES

1. Commander, Naval Air Systems Command, PMR Requirements for Program Element 6.52.02.28.2N FY 1969, PMR Material Transmittal Serial 3199 of 21 September 1967.

2. Barton, D. K., "Final Report: Instrumentation Radar AN/FPS-16(XN-1), Evaluation and Analysis of Radar Performance," Radio Corporation of America, Contract DA-36-034-ORD-151.

3. Barton, D. K., "Radar System Analysis," Prentice-Hall, Inc., 1964.

4. Mills, A. J., et al, "Final Report on Instrumentation Radar AN/FPS-16 (XN-2)," Radio Corporation of America, BuAir Contract NOAS 55-869C.

5. Hoffman, L. A., Wintraub, H. I., Garber, W. A., "Propagation Observations at 3.2 Millimeters," Proceedings IEEE, Vol. 54, No. 4, p. 449, April 1966.

6. Lefande, R. A., "Attenuation of Microwave Radiation for Paths Through the Atmosphere," NRL Report No. 6766, November 29, 1968.

7. Ohman, G. P., "Universal Curves for the Vertical Polarization Reflection Coefficient," IRE Trans., Vol. AP-5, No. 1, January 1957, p. 140.

8. Barton, D. K., Ward, H. R., "Handbook of Radar Measurement," Prentice-Hall, Inc., 1969.

9. Barton, D. K., "Accuracy of a Monopulse Radar," 3rd National Convention on Military Electronics, 1959 Conference Proceedings, Professional Group on Military Electronics Institute of Radio Engineers.

10. McHenry, J. P., Gilkey, J. Y., Whalen, P. K., "Radar Requirements of the Pacific Missile Range," Stanford Research Institute, Contract N00019-67-C-0411, March 1968.

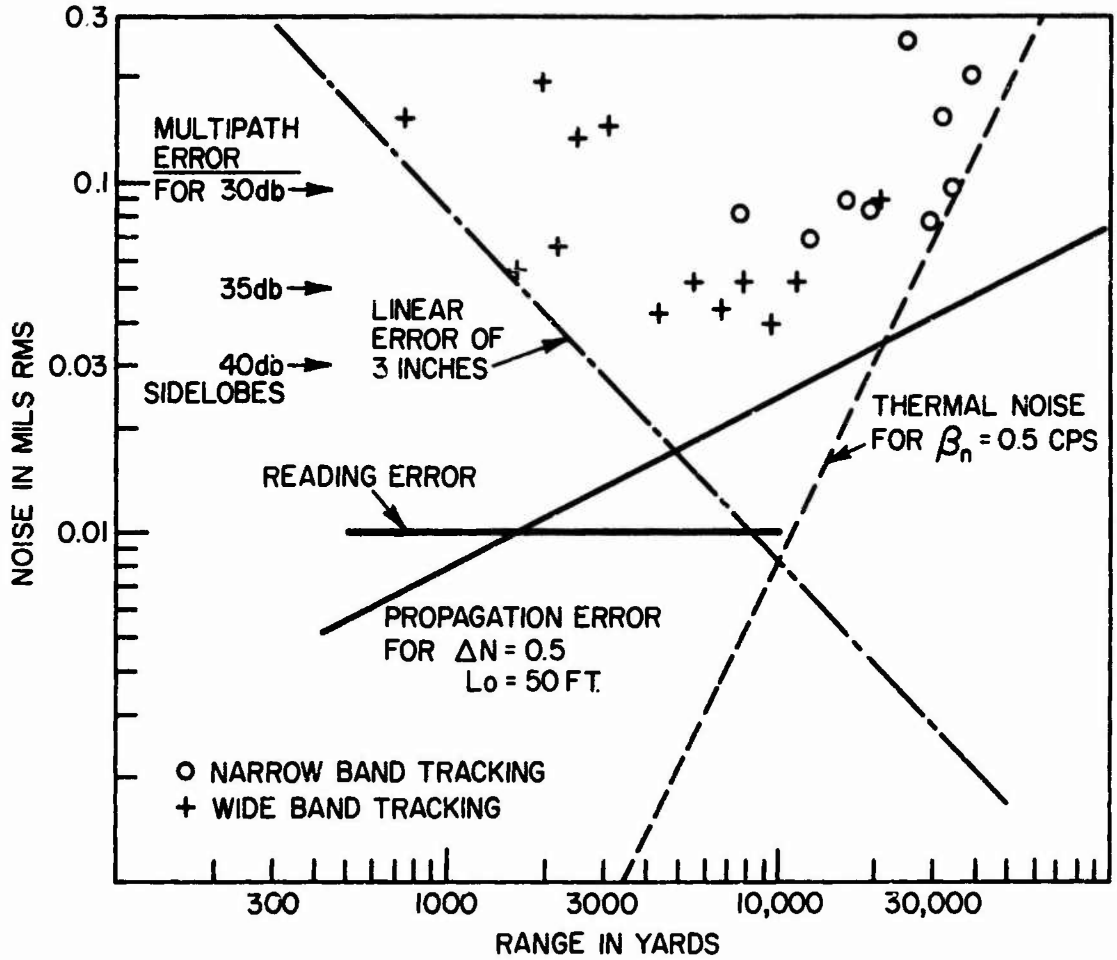

Fig. 1 - Elevation-angle tracking error of the AN/FPS-16 (XN-1) radar

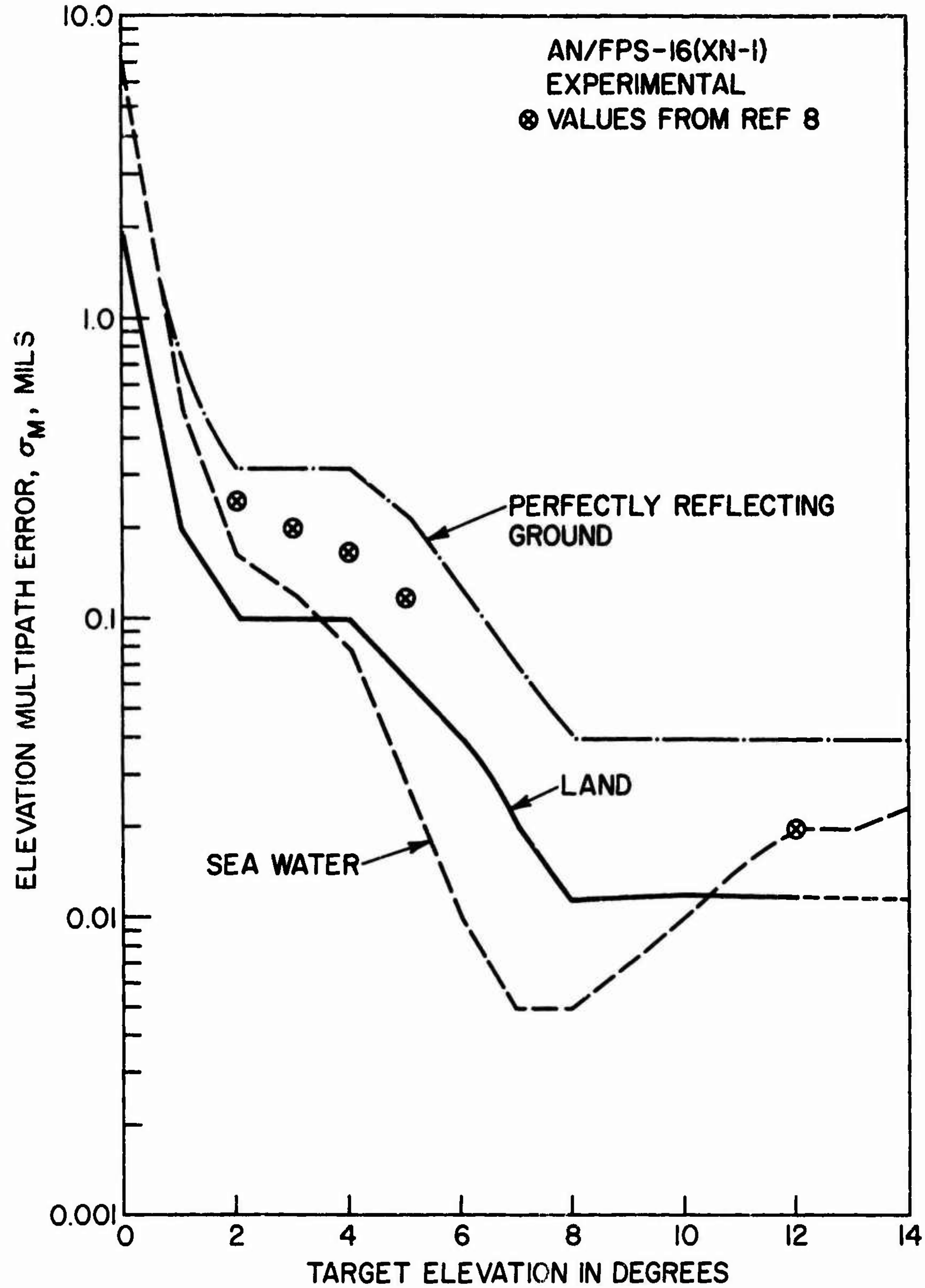

Fig. 2 - Elevation-angle multipath error of the AN/FPS-16 (XN-2) radar

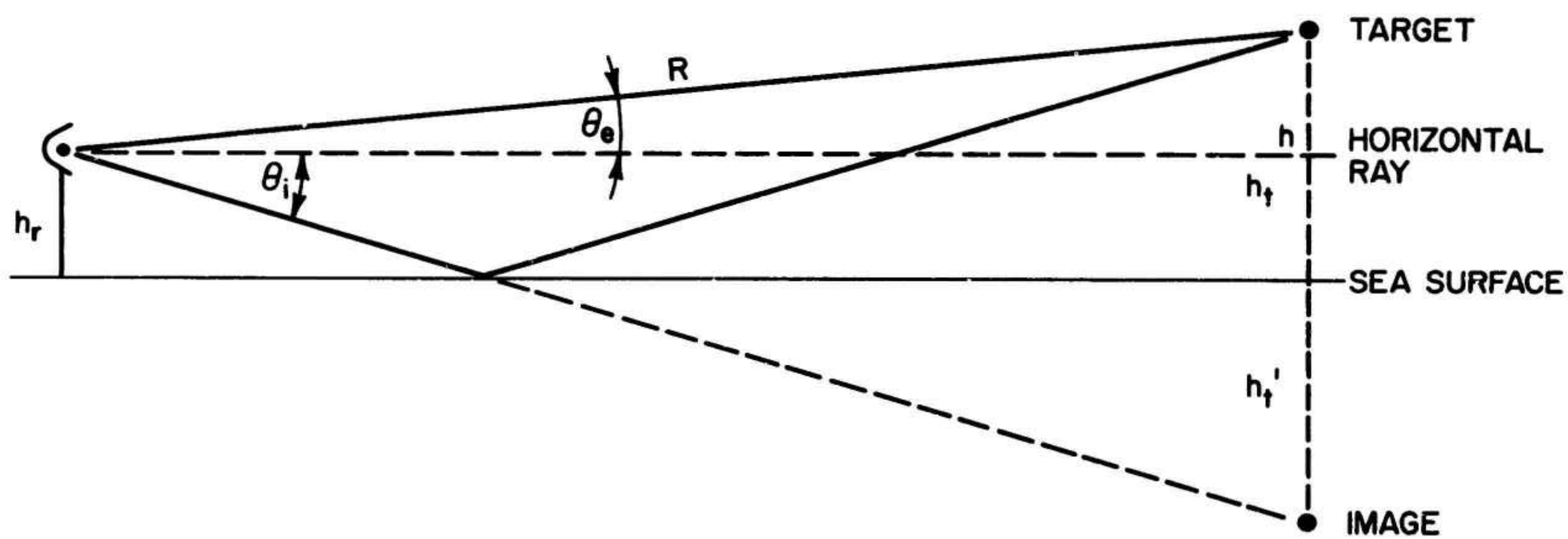

Fig. 3 - Propagation over a flat surface

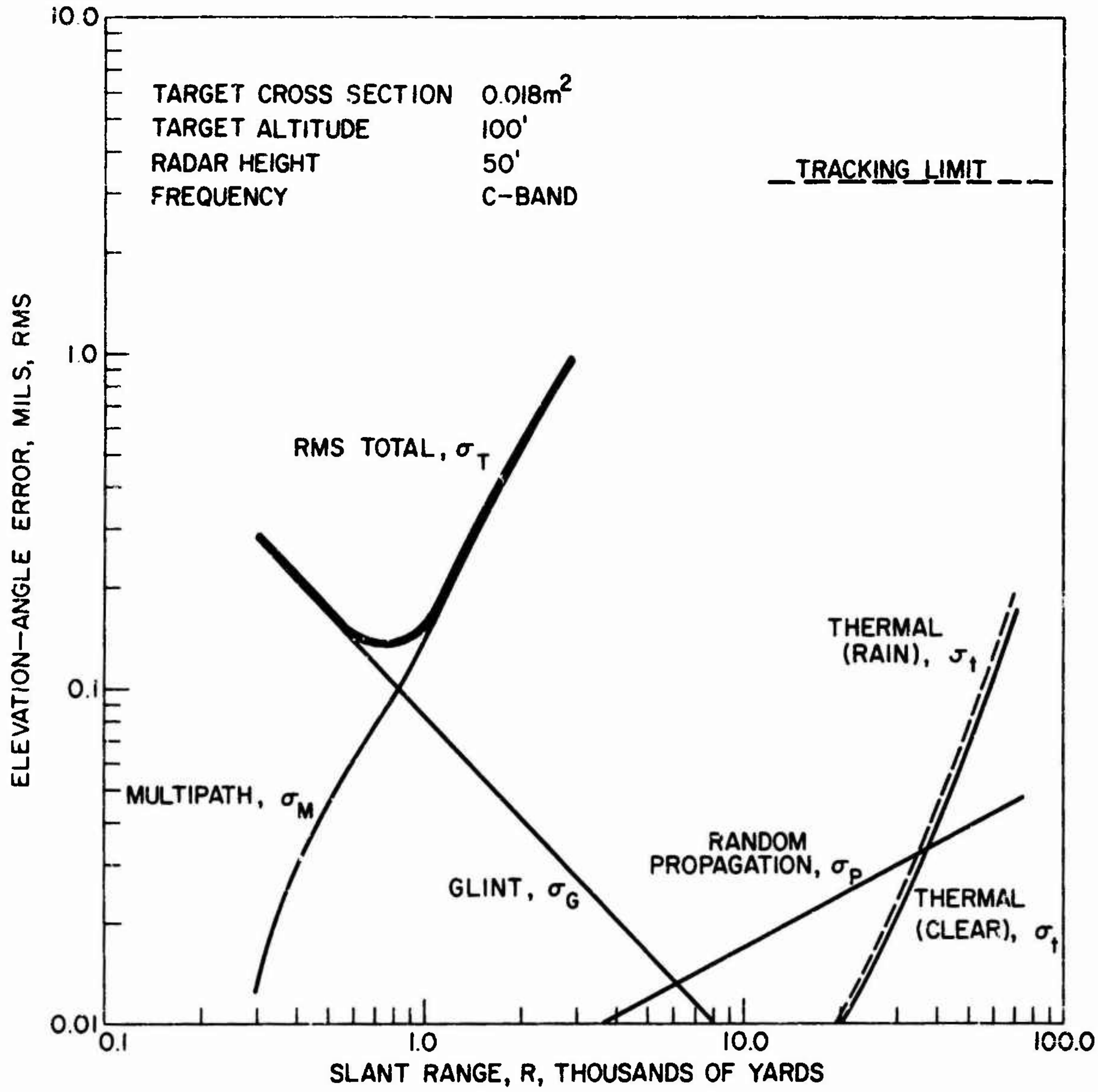

Fig. 4 - RMS elevation-angle tracking noise at C-band over smooth water

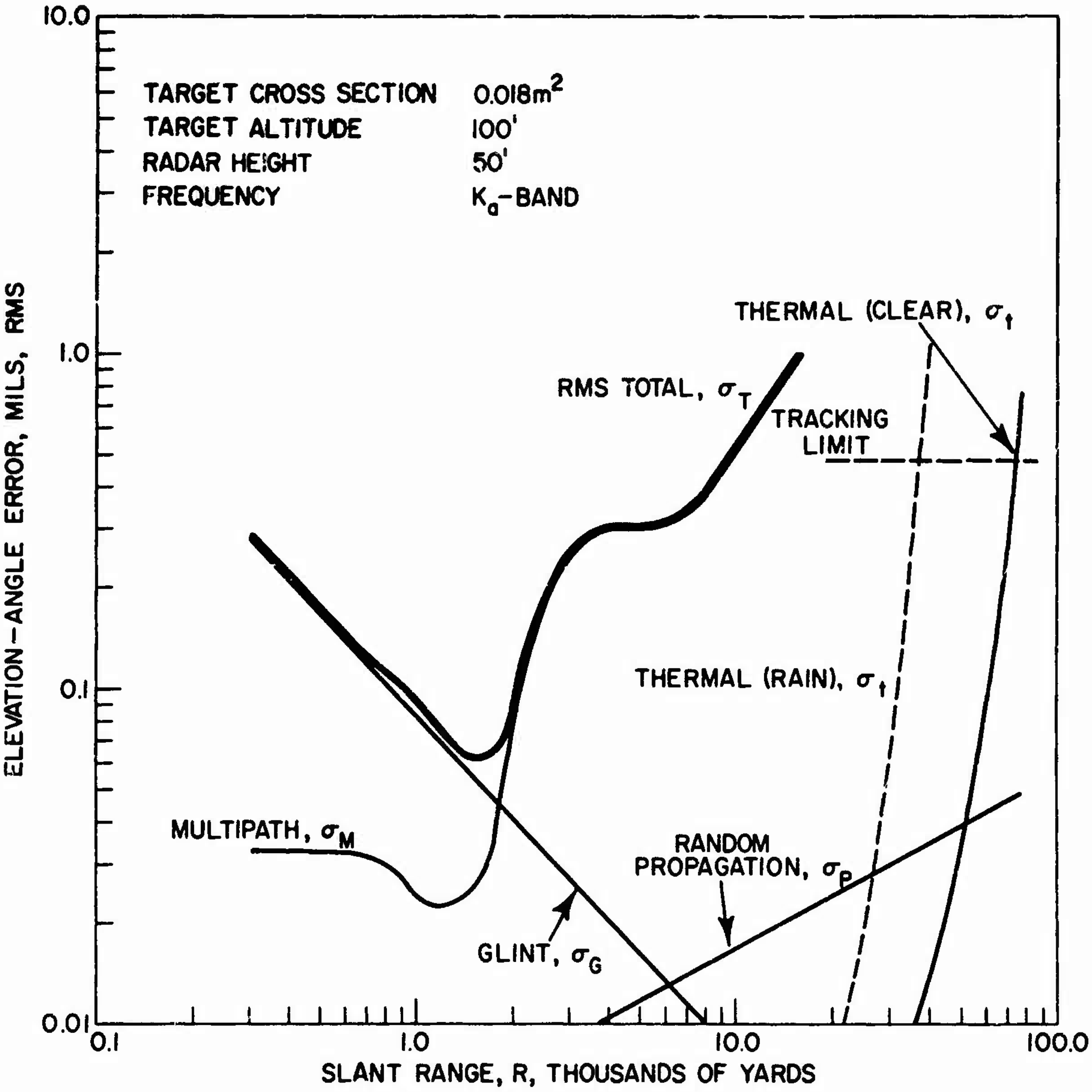

Fig. 5 - RMS elevation-angle tracking noise at K_a-band over smooth water

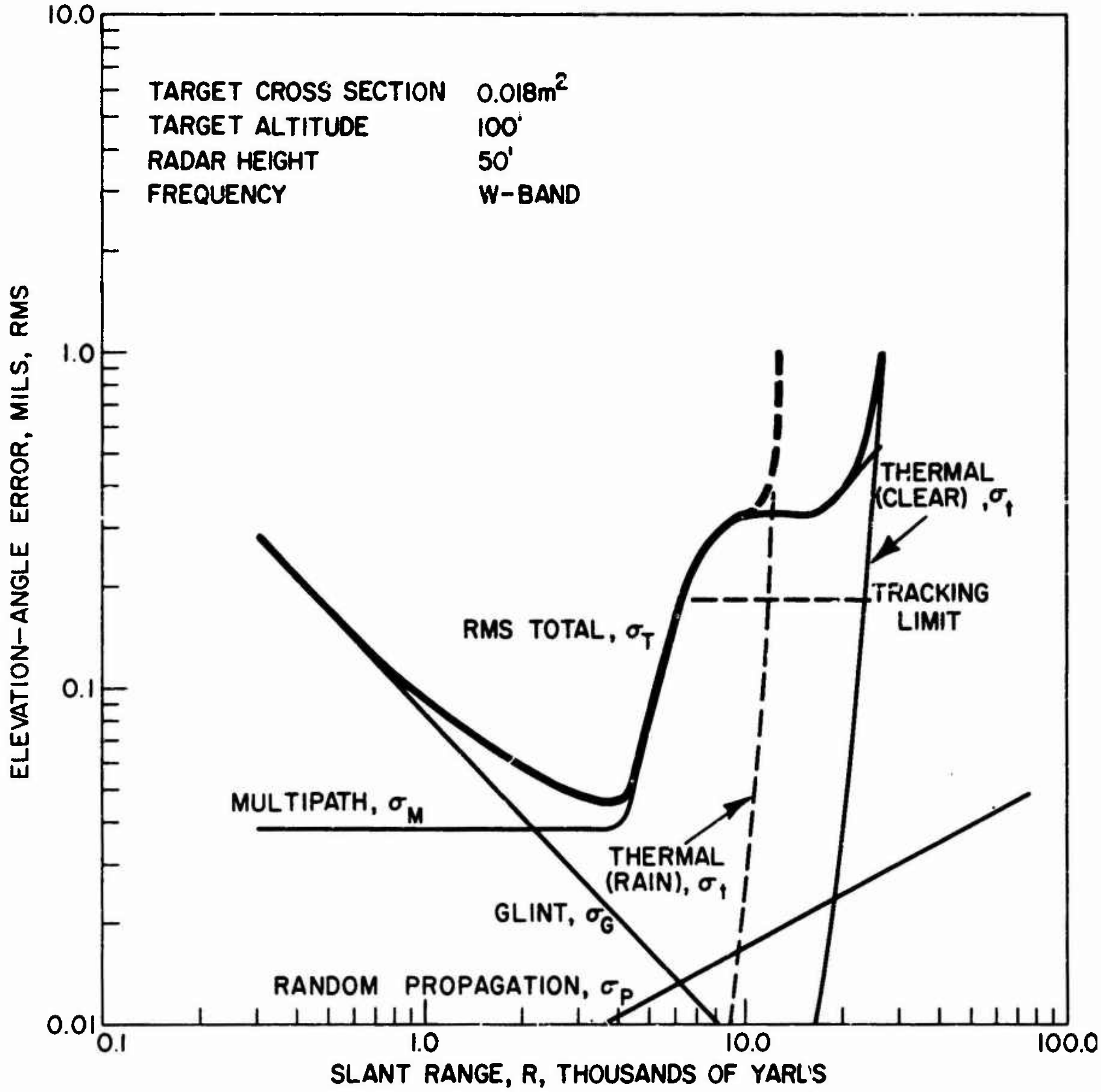

Fig. 6 - RMS elevation-angle tracking noise at W-band over smooth water

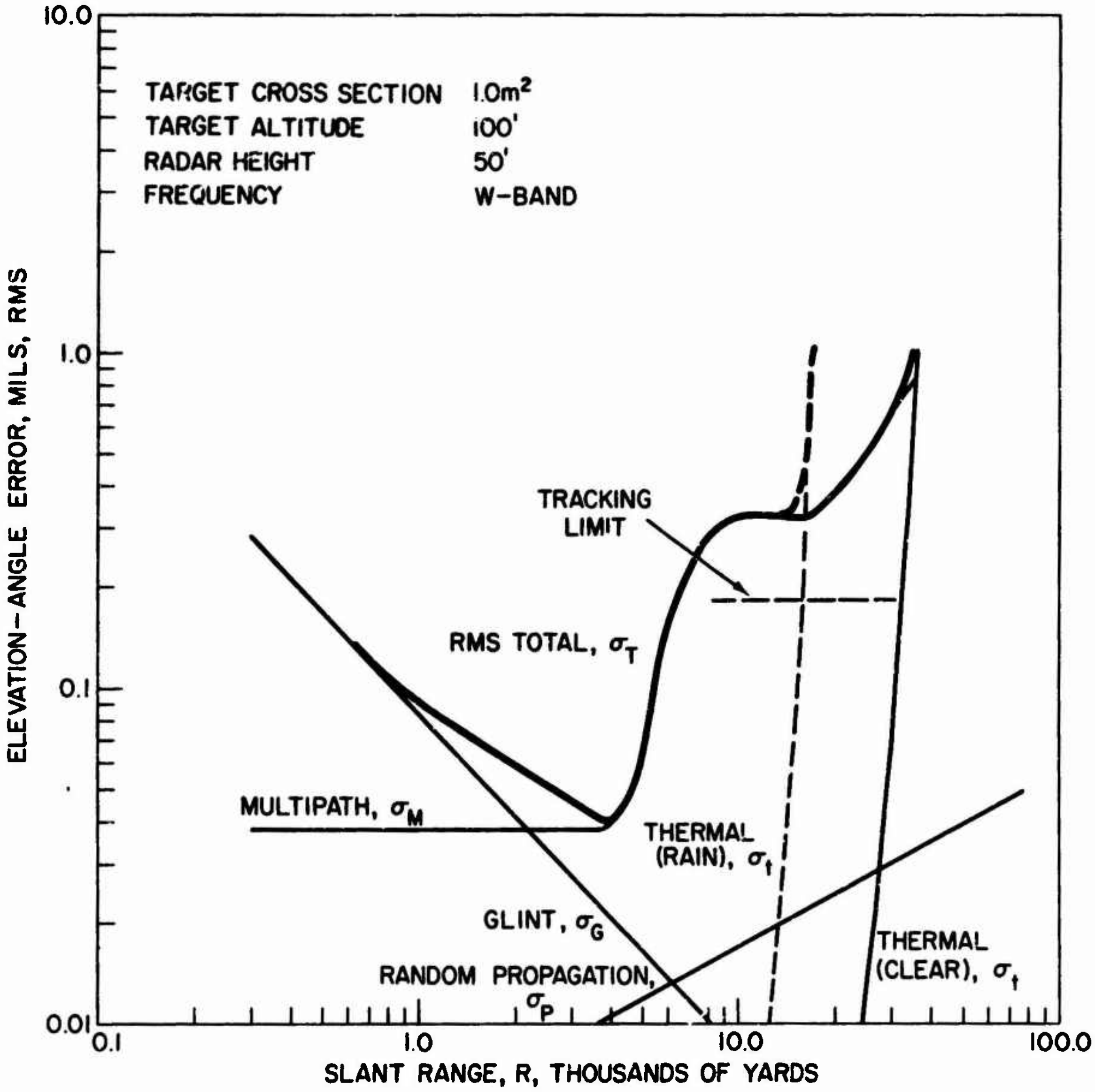

Fig. 7 - RMS elevation-angle tracking noise at W-band over smooth water

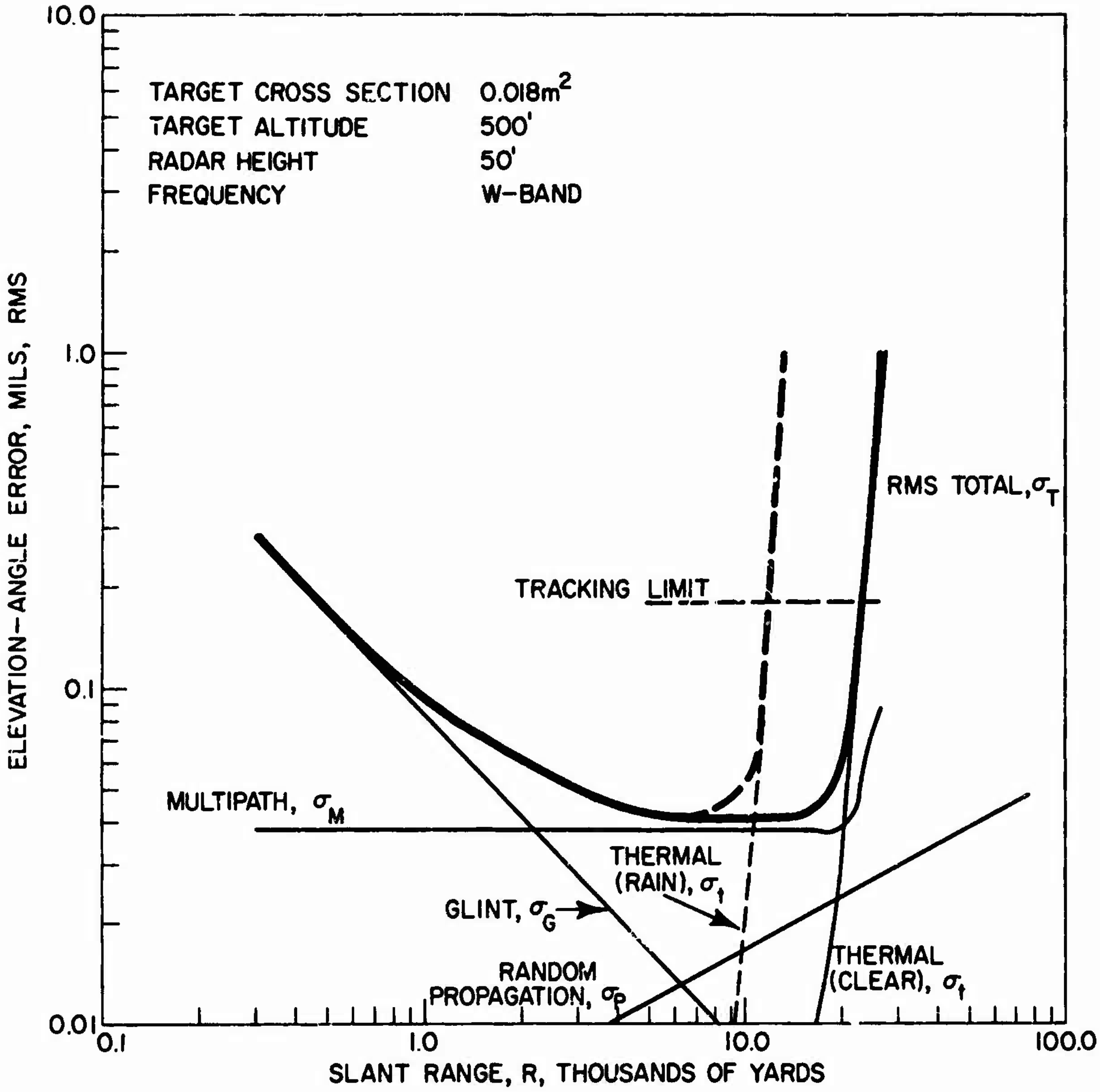

Fig. 8 - RMS elevation-angle tracking noise at W-band over smooth water

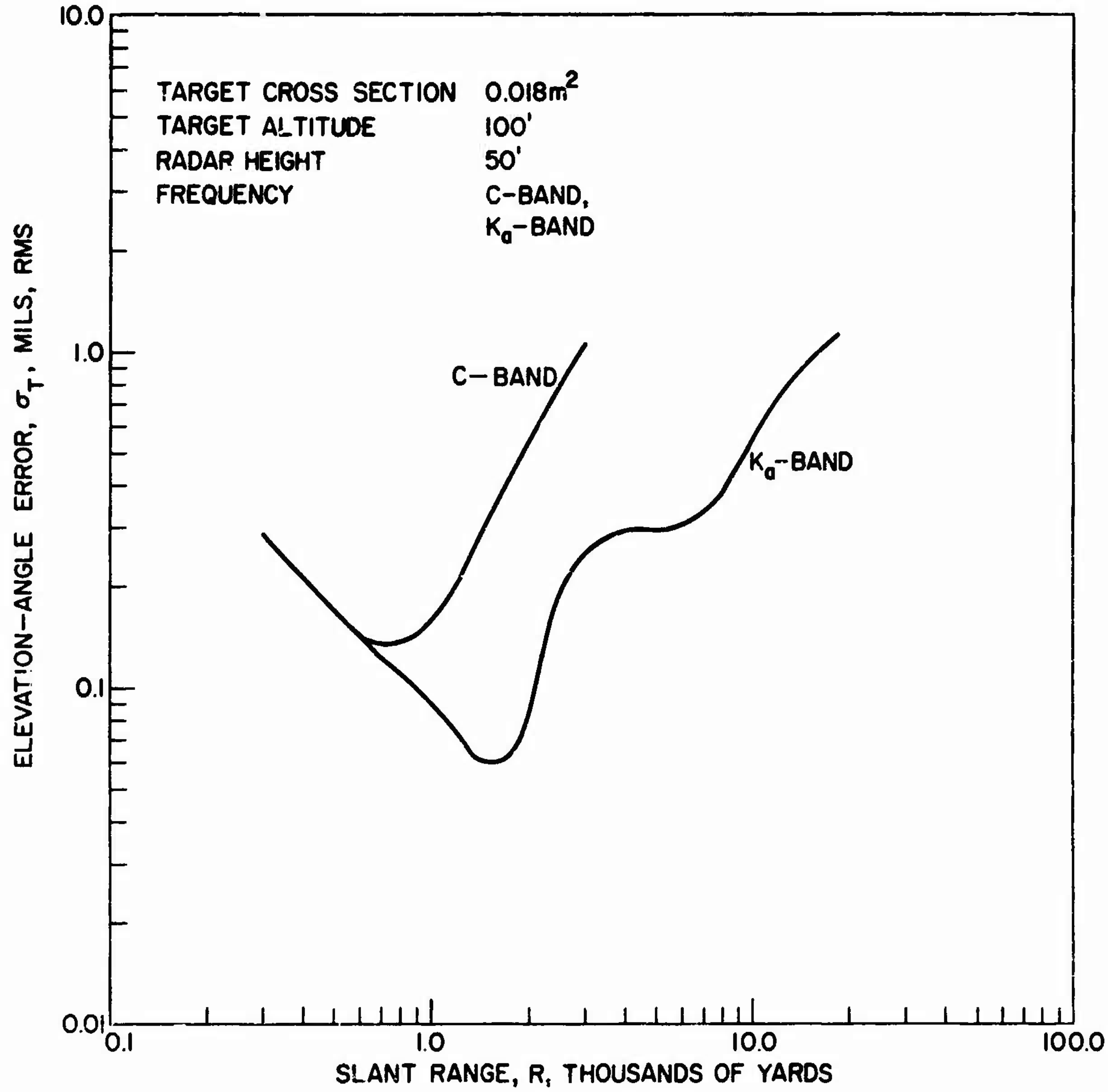

Fig. 9 - Total RMS elevation-angle tracking noise at C and K_a-band over smooth water

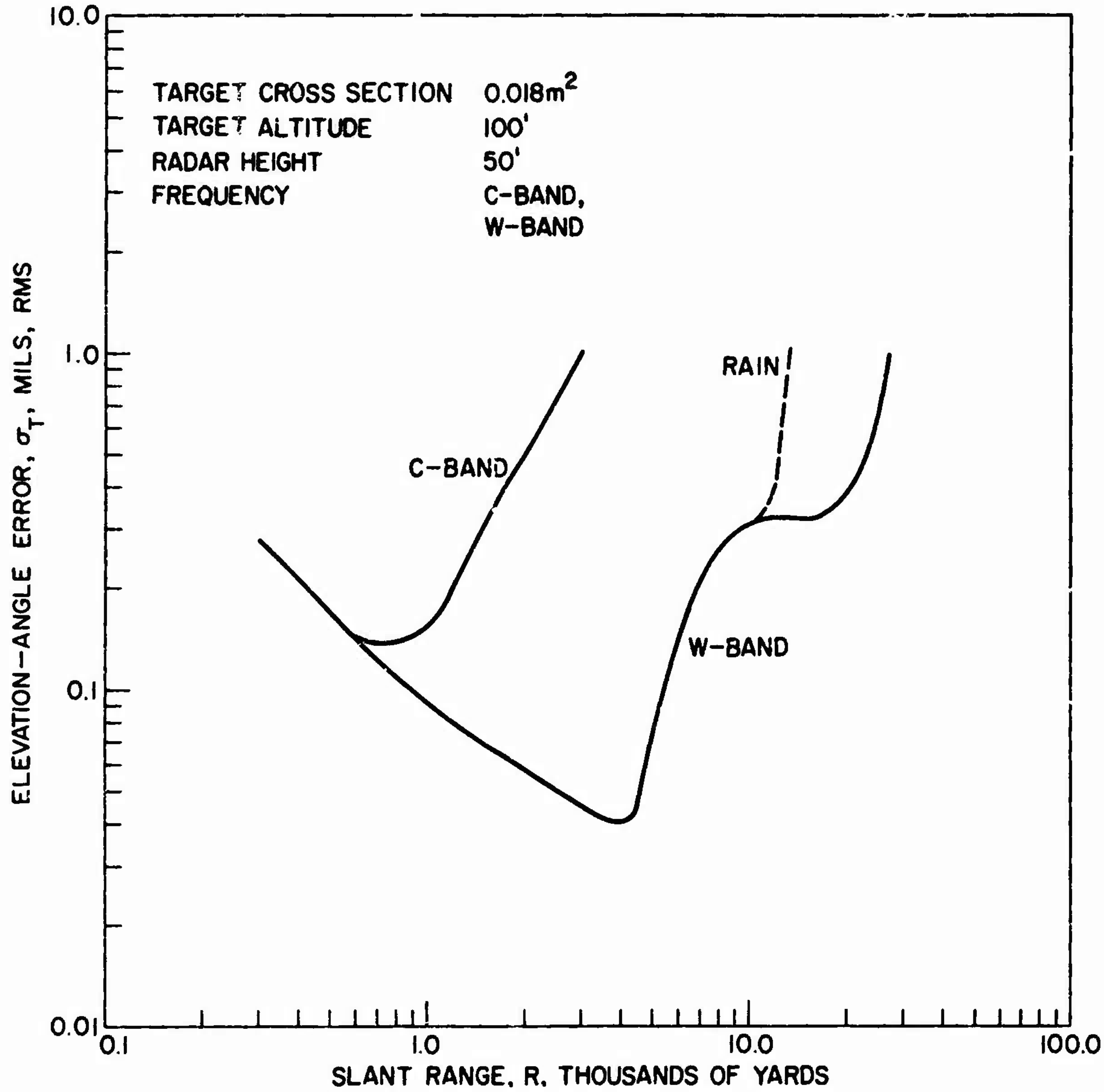

Fig. 10 - Total RMS elevation-angle tracking noise at C and W-band over smooth water

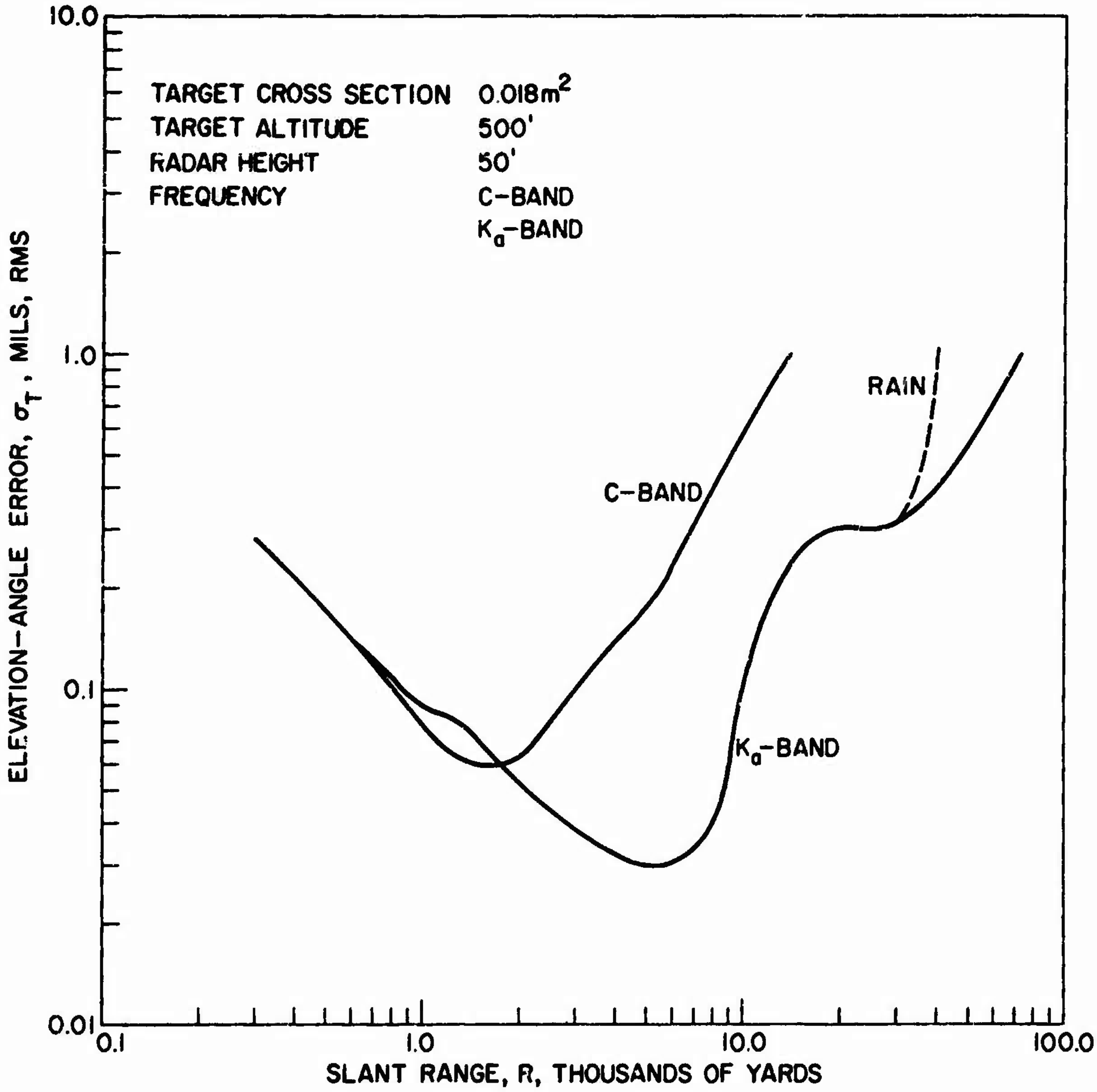

Fig. 11 - Total RMS elevation-angle tracking noise at C and K_a-band over smooth water

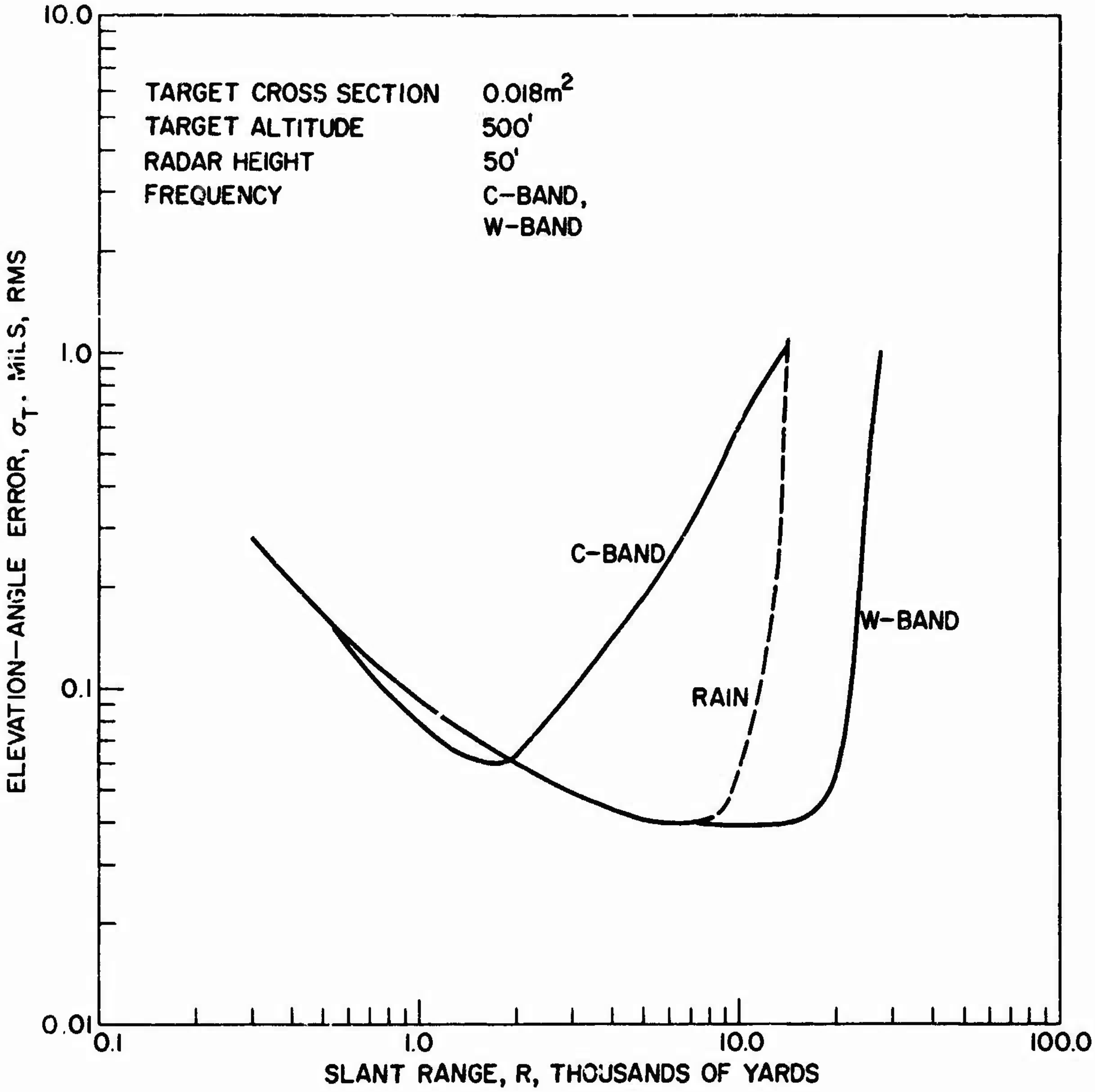

Fig. 12 - Total RMS elevation-angle tracking noise at C and W-band over smooth water

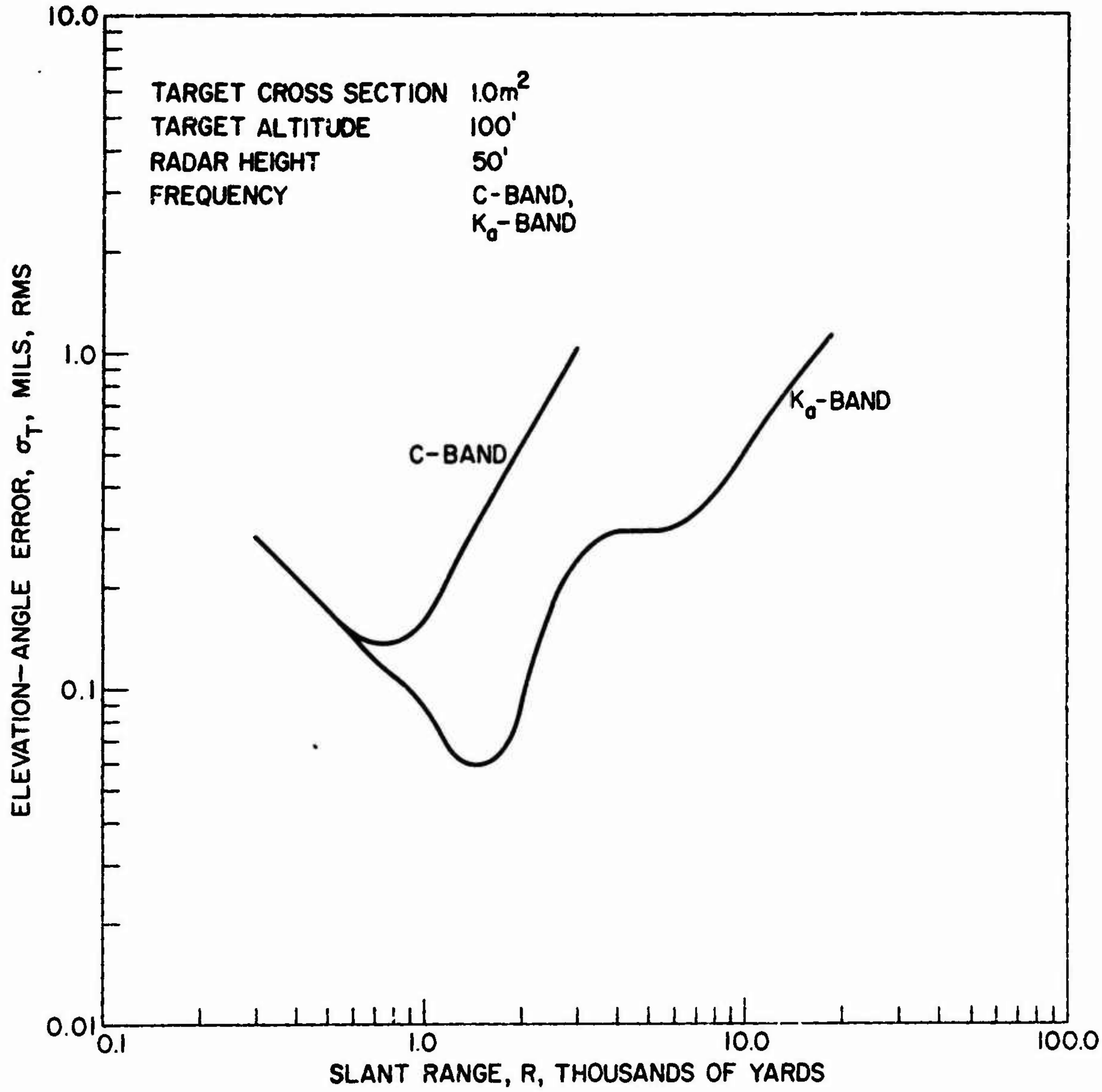

Fig. 13 - Total RMS elevation-angle tracking noise at C and K_a-band over smooth water

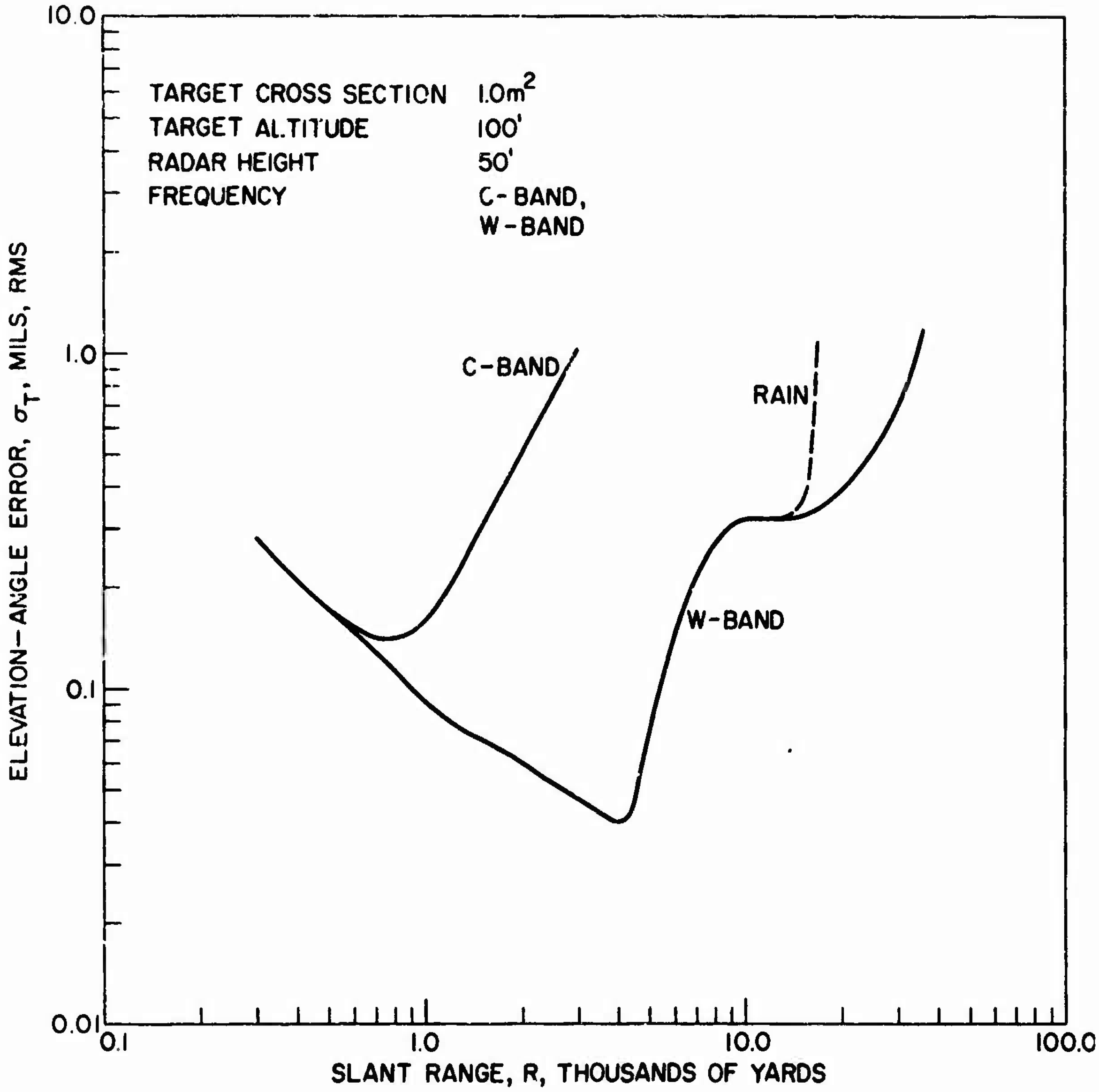

Fig. 14 - Total RMS elevation-angle tracking noise at C and W-band over smooth water

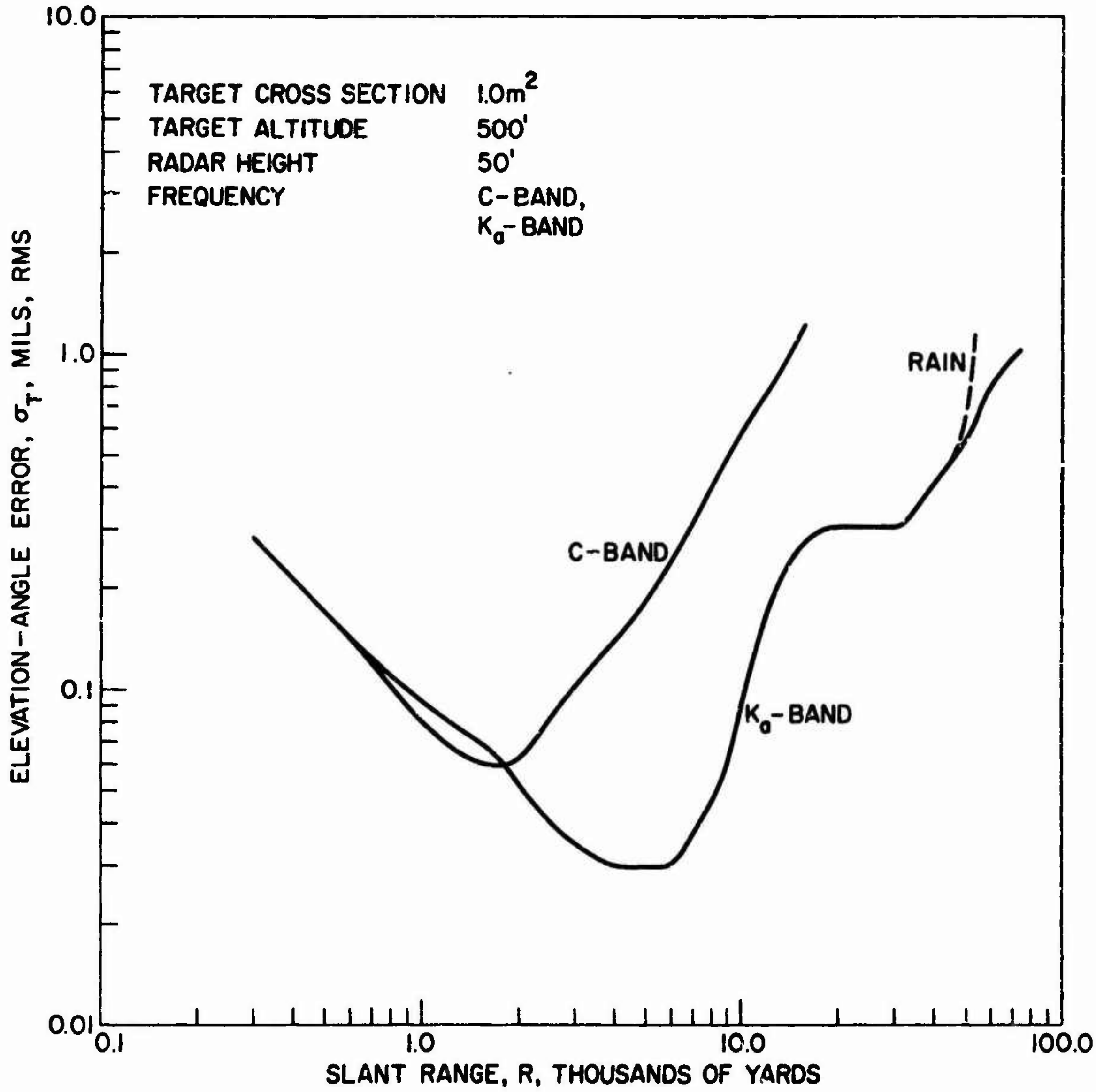

Fig. 15 - Total RMS elevation-angle tracking noise at C and K_a-band over smooth water

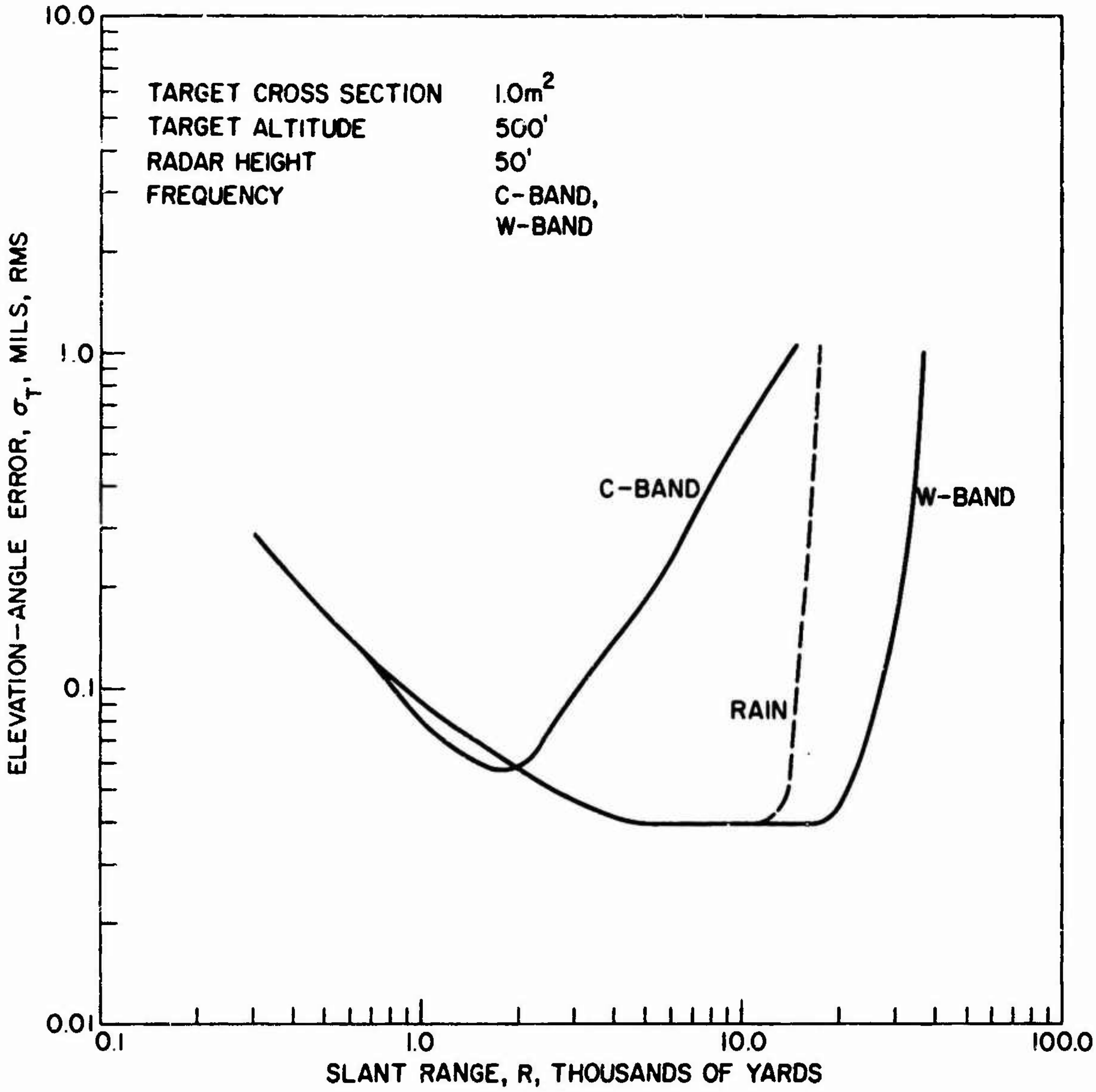

Fig. 16 - Total RMS elevation-angle tracking noise at C and W-band over smooth water

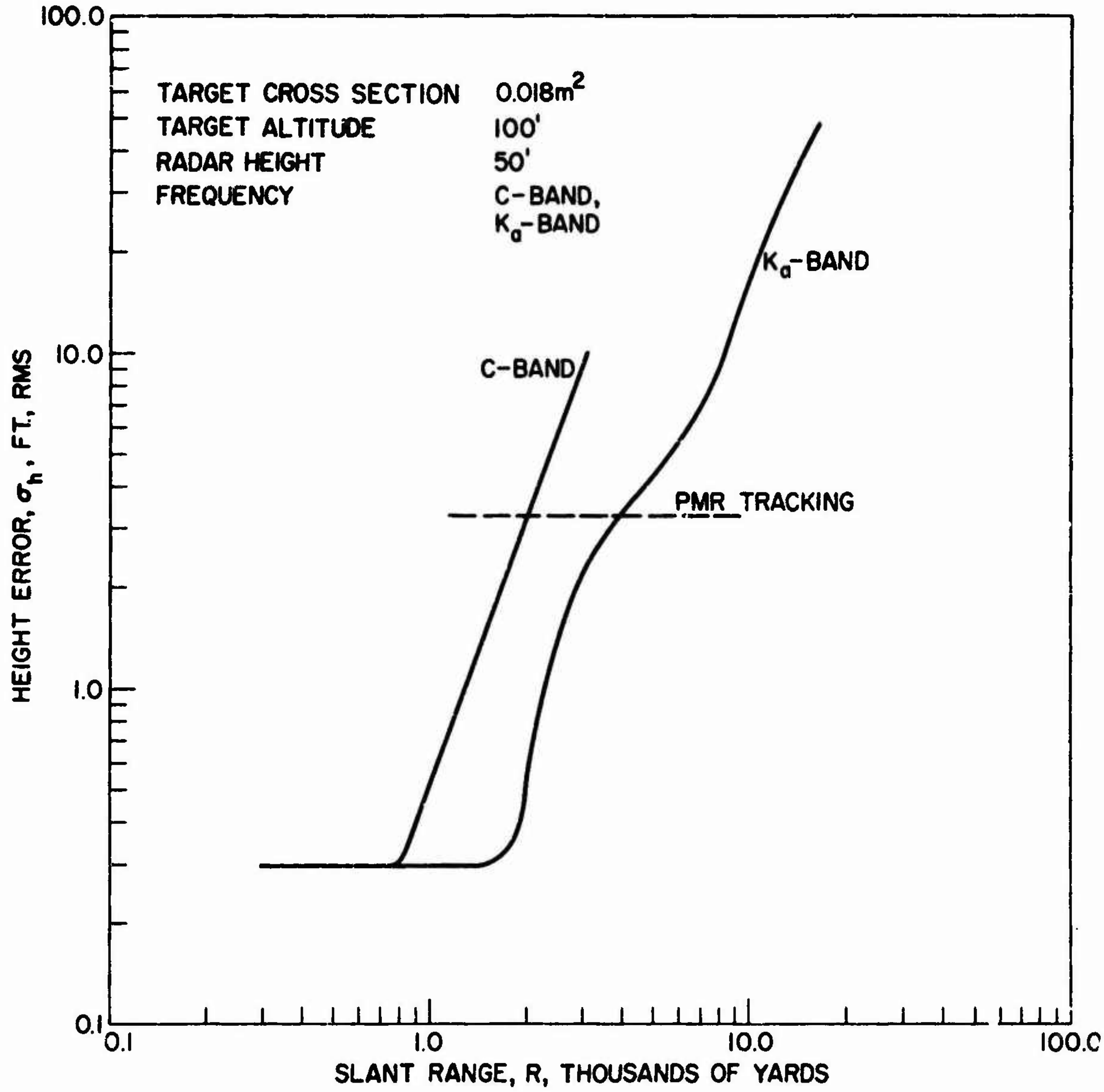

Fig. 17 - Total height error at C and K_a-band over smooth water

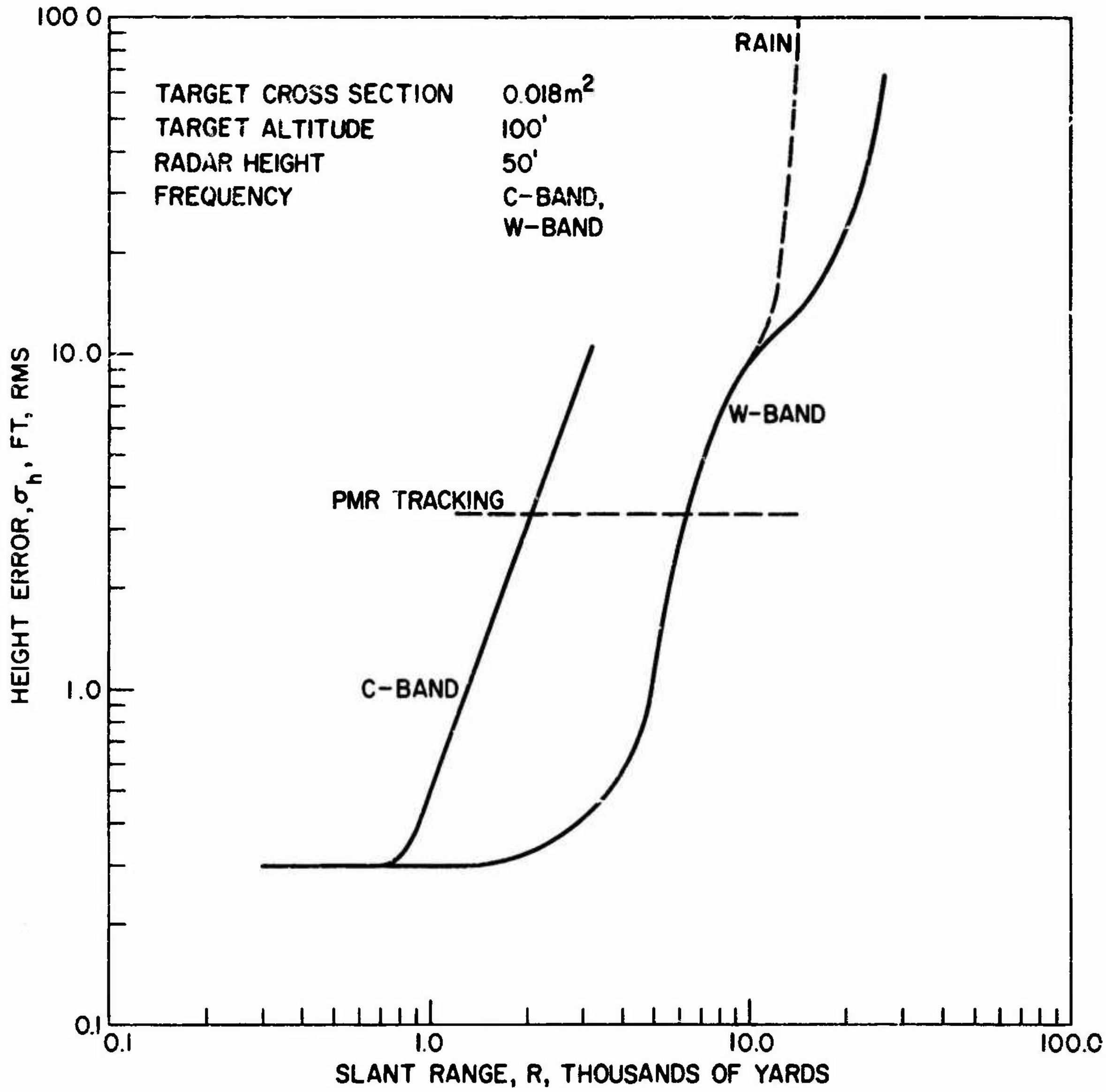

Fig. 18 - Total height error at C and W-band over smooth water

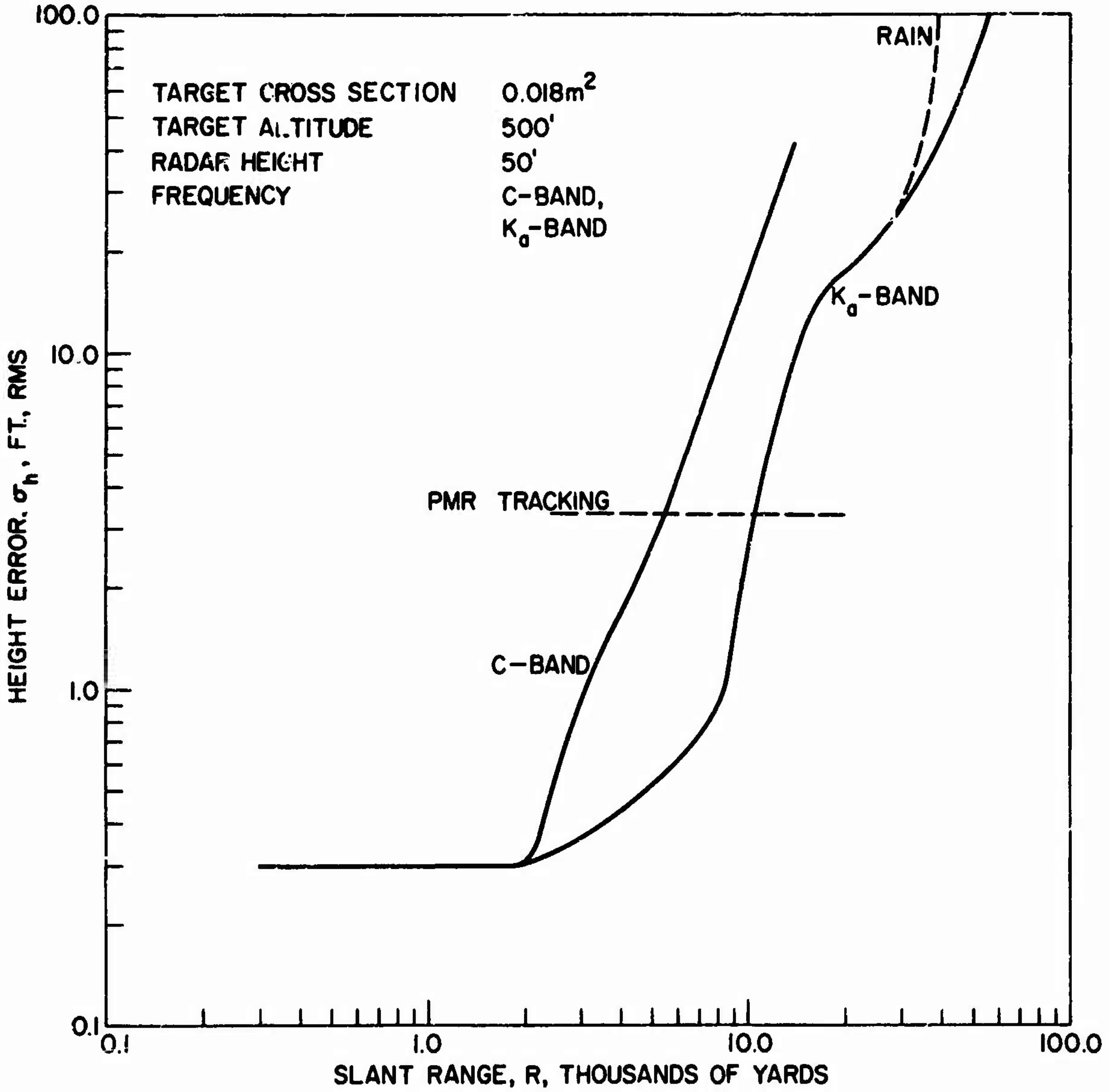

Fig. 19 - Total height error at C and K_a-band over smooth water

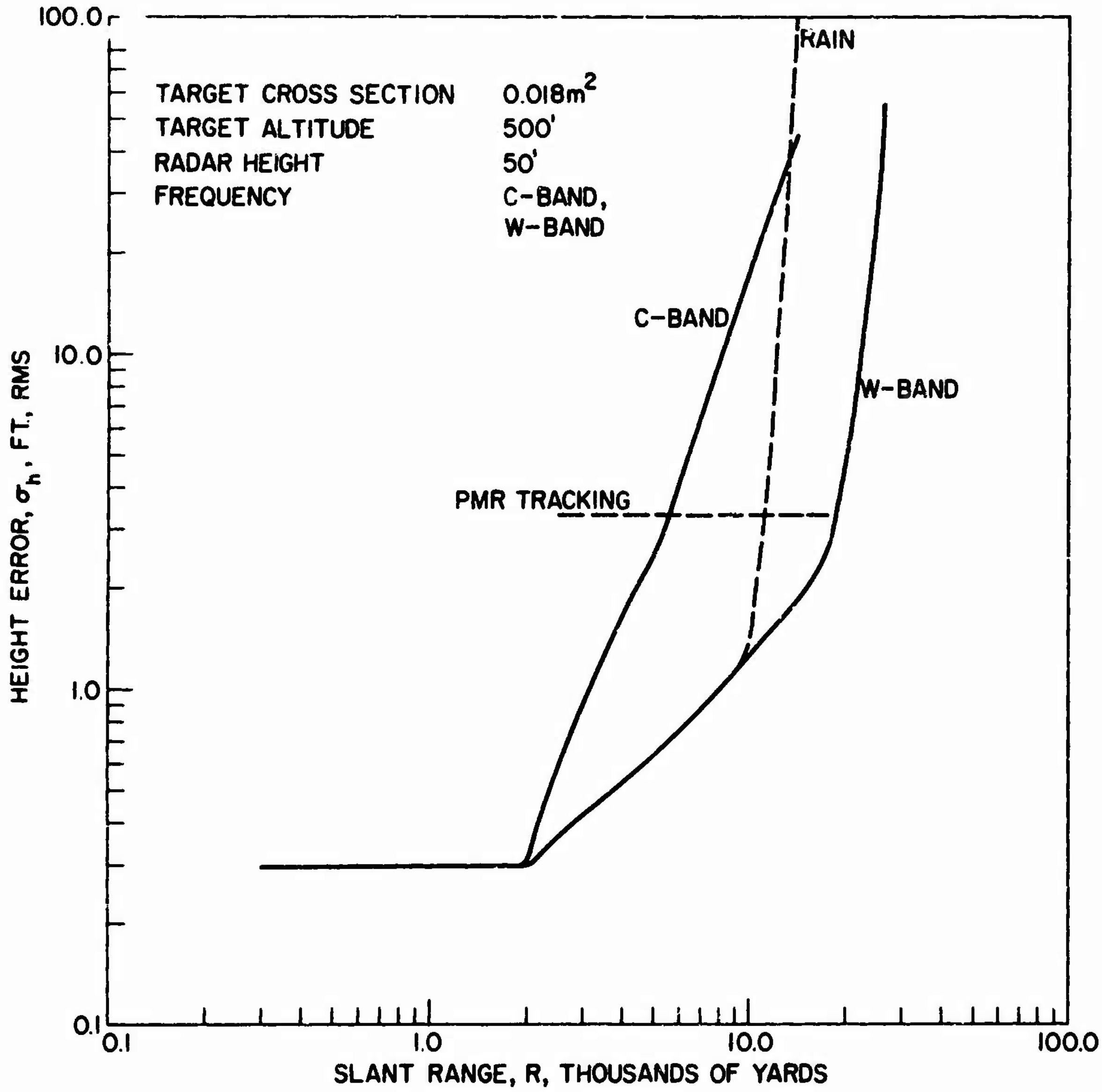

Fig. 20 - Total height error at C and W-band over smooth water

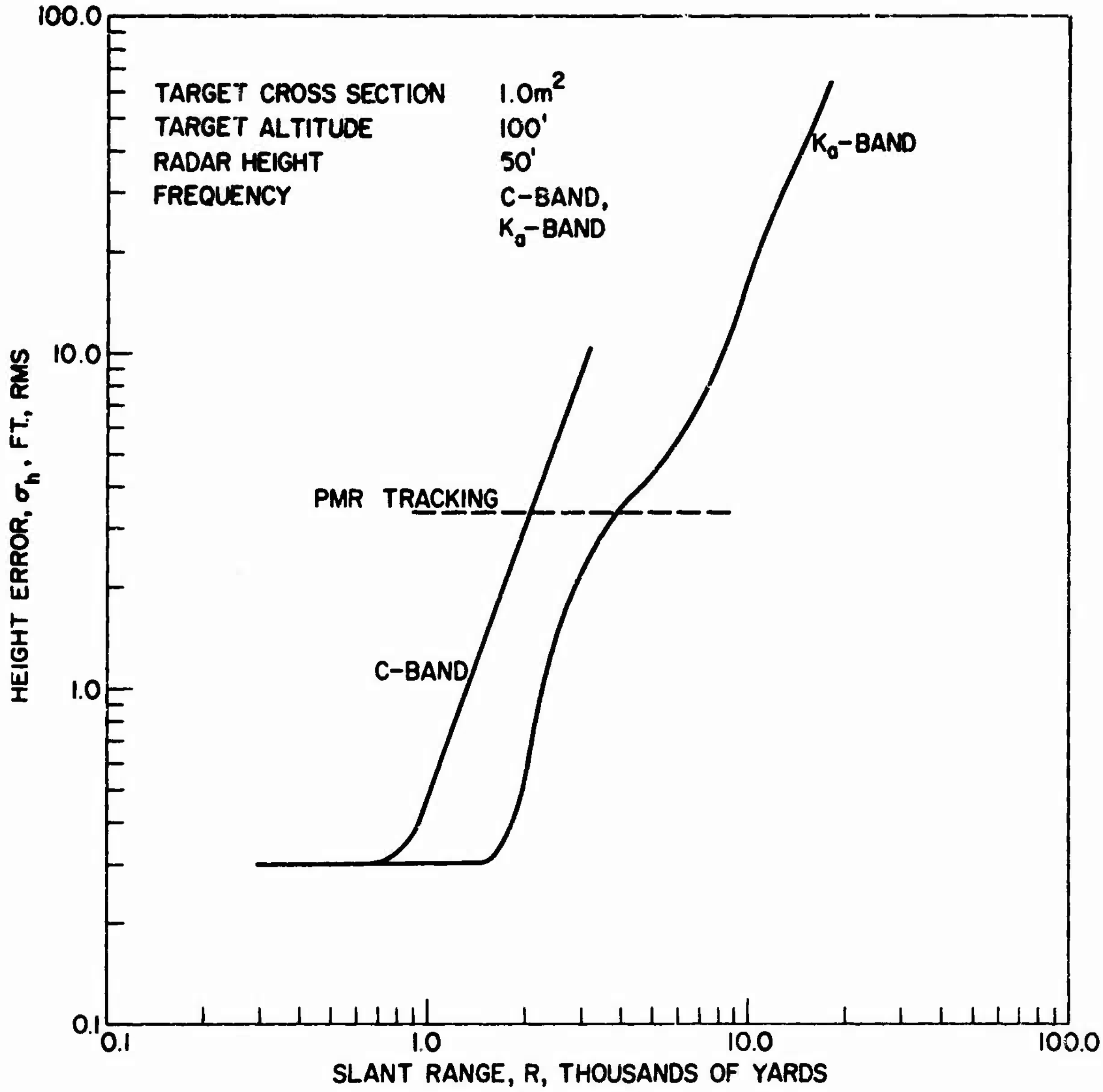

Fig. 21 - Total height error at C and K_a-band over smooth water

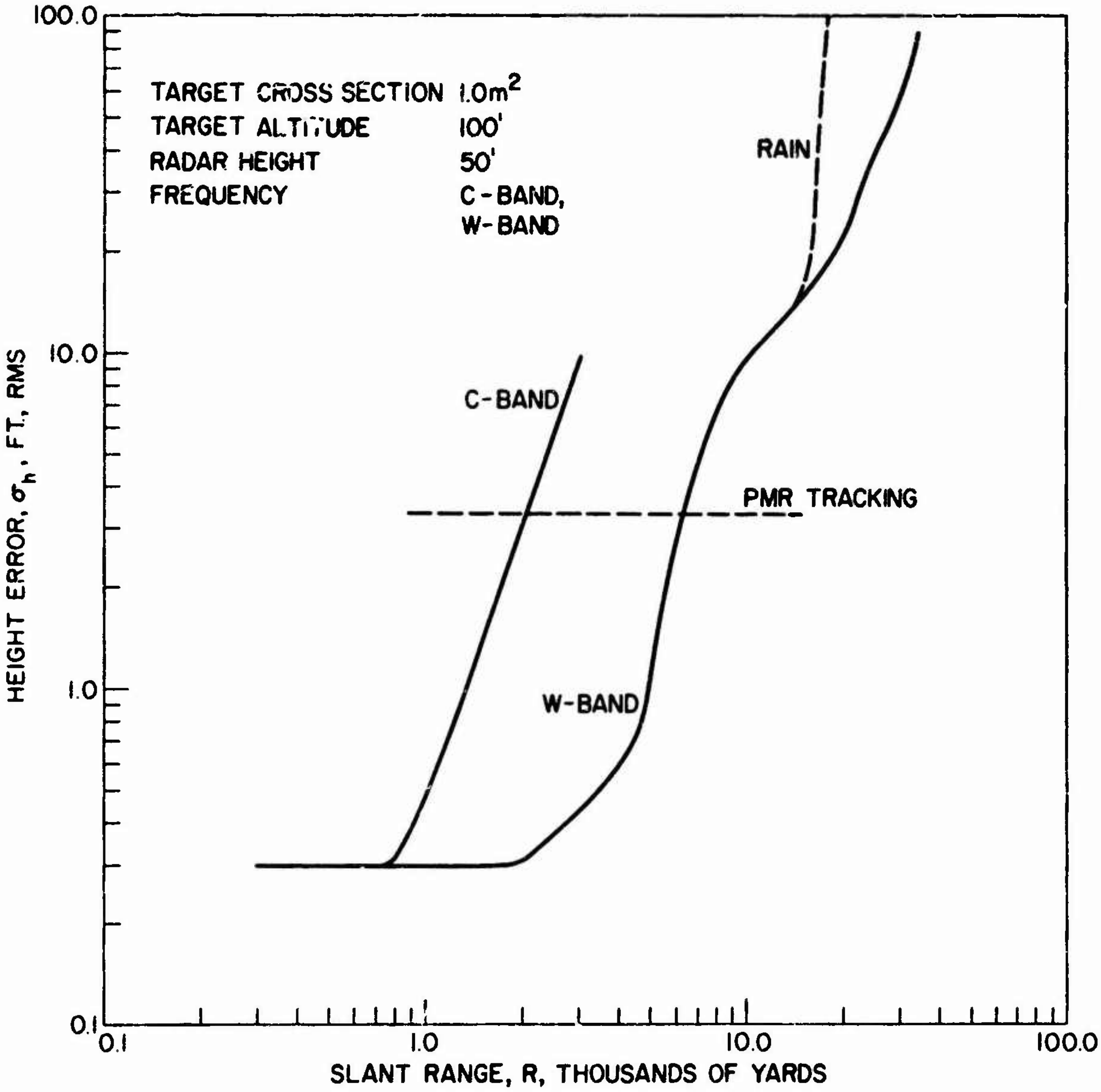

Fig. 22 - Total height error at C and W-band over smooth water

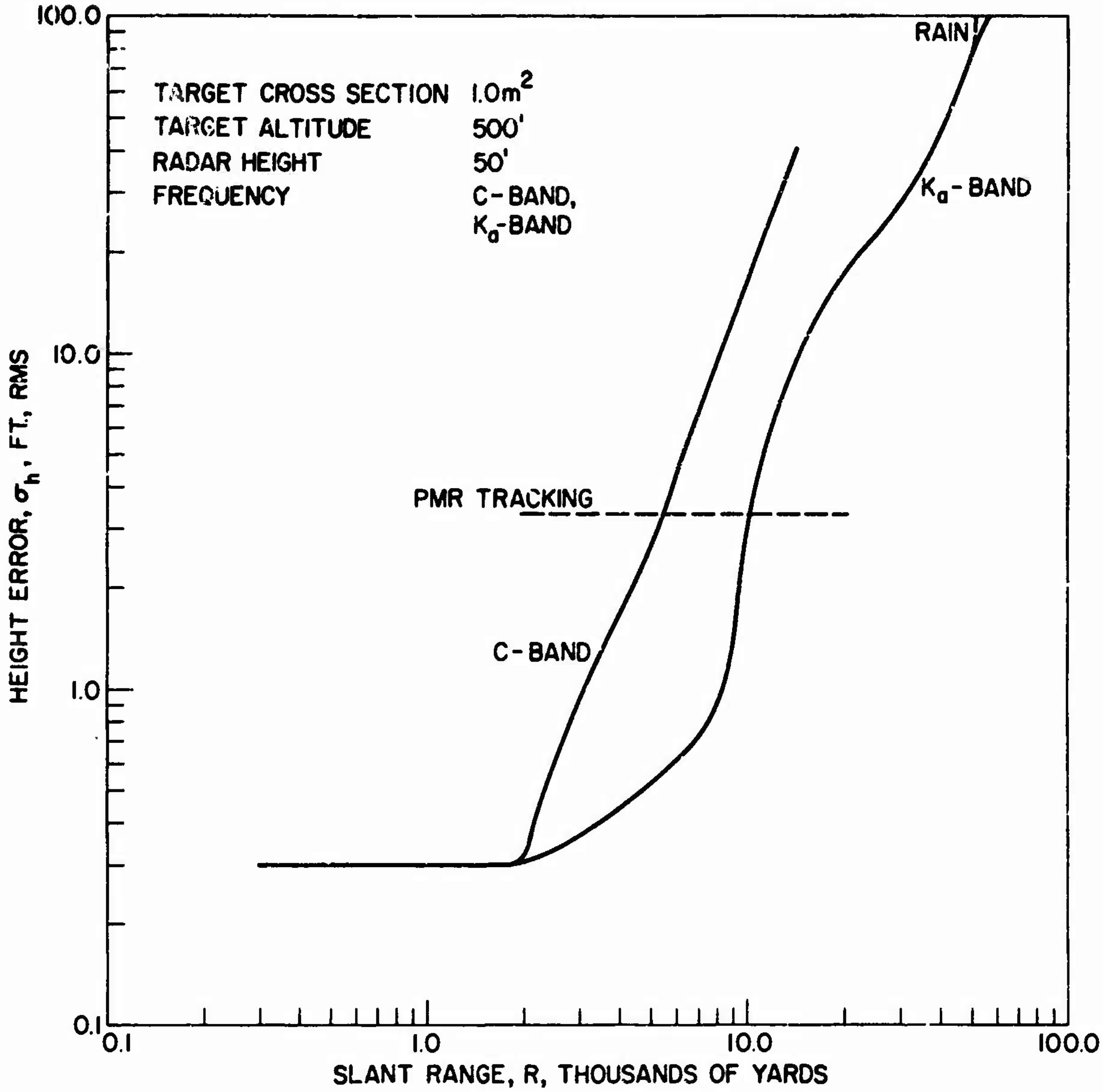

Fig. 23 - Total height error at C and K_a-band over smooth water

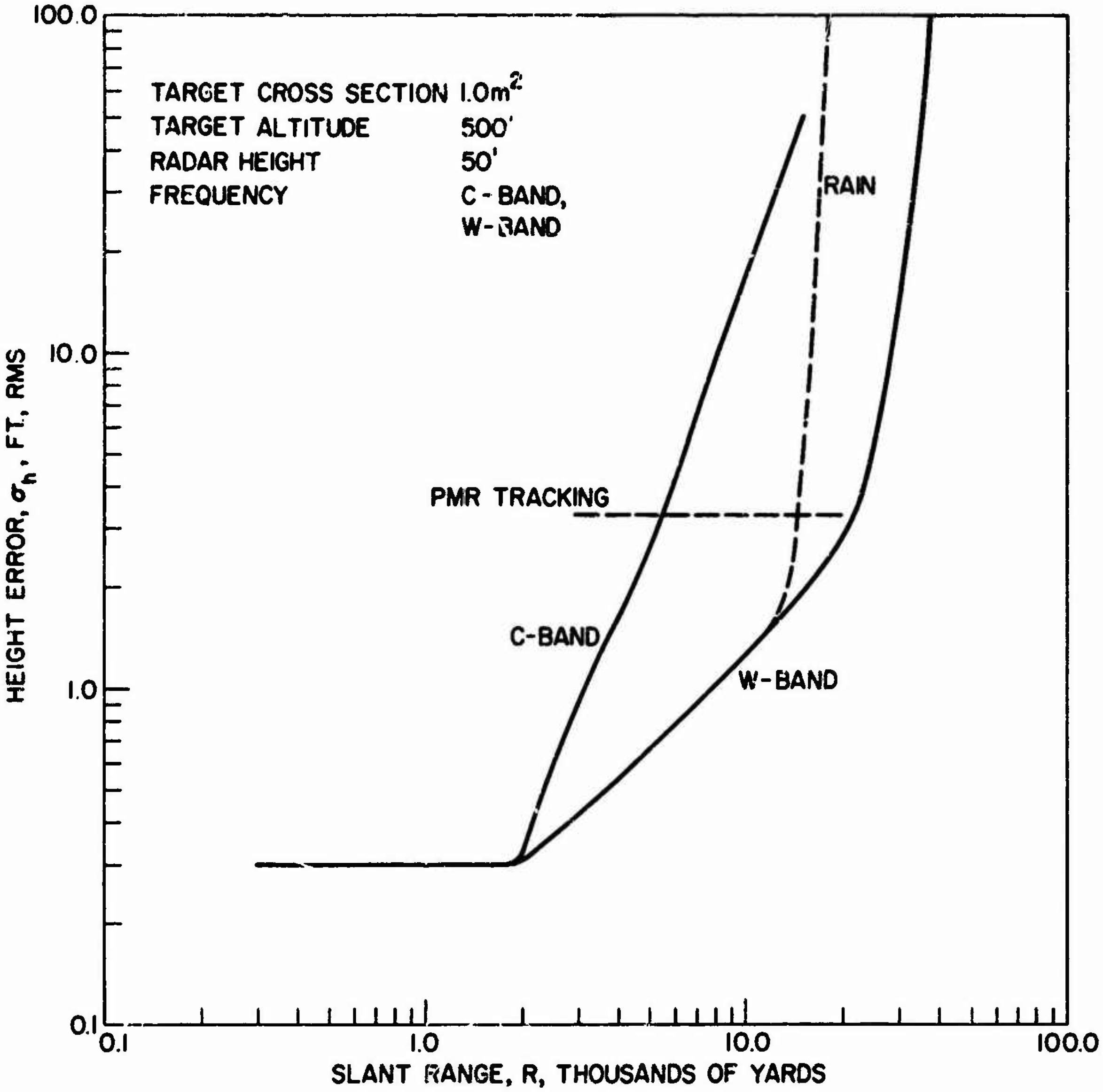

Fig. 24 - Total height error at C and W-band over smooth water